NASA CONTRACTOR REPORT

NASA CR-19

NASA CR-1925

CALCULATION OF TURBULENT BOUNDARY LAYERS WITH HEAT TRANSFER AND PRESSURE GRADIENT UTILIZING A COMPRESSIBILITY TRANSFORMATION

Part III - Computer Program Manual

by J. Schneider and J. Boccio

Prepared by
GENERAL APPLIED SCIENCE LABORATORIES, INC.
Westbury, L. I., New York 11590

for Langley Research Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JANUARY 1972

1. Report No. NASA CR-1925	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle CALCULATION OF TURBULENT BOUNDARY LAYERS WITH HEAT TRANSFER AND PRESSURE GRADIENT UTILIZING A COMPRESSIBILITY TRANSFORMATION - PART III - COMPUTER PROGRAM MANUAL		5. Report Date January 1972
		6. Performing Organization Code
7. Author(s) J. Schneider and J. Boccio		8. Performing Organization Report No. GASL TR-748 Part III
9. Performing Organization Name and Address General Applied Science Laboratories, Inc. A Subsidiary of the Marquardt Company Westbury, L.I.; New York 11590		10. Work Unit No.
		11. Contract or Grant No. NAS1-9624
		13. Type of Report and Period Covered CONTRACTOR REPORT
12. Sponsoring Agency Name and Address NATIONAL AERONAUTICS AND SPACE ADMINISTRATION WASHINGTON, D.C. 20546		14. Sponsoring Agency Code

15. Supplementary Notes

A description of the problem formulation and development of the describing differential equations is presented in Parts I and II of this report.

16. Abstract This manual describes a new computer program capable of determining the properties of a compressible turbulent boundary layer with pressure gradient and heat transfer. The program treats the two-dimensional problem assuming perfect gas and Crocco integral energy solution. A compressibility transformation is applied to the equation for the conservation of mass and momentum, which relates this flow to a low speed constant property flow with simultaneous mass transfer and pressure gradient. The resulting system of describing equations consists of eight ordinary differential equations which are solved numerically.

17. Key Words (Suggested by Author(s)) Turbulent boundary layer; Heat transfer; Pressure gradient; Computer programs	18. Distribution Statement Unclassified - Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	98	$3.00

*For sale by the National Technical Information Service, Springfield, Virginia 22151

FOREWORD

The present report is one of a series of three reports describing a new computer program which predicts turbulent boundary layer behavior for a condition involving both heat transfer and pressure gradient. Part I serves as a summary report and describes the general analysis which is utilized in the numerical calculation scheme. In Part II the requisite low speed formulation, consisting of a constant property flow with combined pressure gradient and mass transfer is described. Part III describes the numerical and computational procedures involved and serves as a computer program manual.

The titles in the series are:

PART I - Summary Report - "Calculation of Turbulent Boundary Layers with Heat Transfer and Pressure Gradient Utilizing a Compressibility Transformation," by C. Economos and J. Boccio.

PART II - "Constant Property Turbulent Boundary Layer Flow with Simultaneous Mass Transfer and Pressure Gradient," by J. Boccio and C. Economos.

PART III - "Computer Program Manual," by J. Schneider and J. Boccio.

This investigation was conducted for the Langley Research Center, National Aeronautics and Space Administration, under Contract No. NAS1-9624, with Mr. Kazimierz Czarnecki as the NASA Technical Monitor.

The contractor's report number is GASL TR-748.

CONTENTS

CALCULATION OF TURBULENT BOUNDARY LAYERS WITH HEAT TRANSFER AND PRESSURE GRADIENT UTILIZING A COMPRESSIBILITY TRANSFORMATION

Part III - Computer Program Manual

by
J. Schneider and J. Boccio
General Applied Science Laboratories, Inc.

I. INTRODUCTION

This manual is the third part of a three-volume report describing a new computer program which predicts turbulent boundary layer behavior under the influence of pressure gradient and heat transfer by means of a compressibility transformation. In this procedure use is made of a second order closure principal which relates the flow of interest to a constant property companion flow in which pressure gradient and mass transfer occur simultaneously.

This manual actually describes the operation of two new programs, the first of which provides the required description in the transformed plane. This program, which is referred to hereafter as PILOT1, treats the incompressible problem with combined pressure gradient and mass transfer for two-dimensional planar flow.

The program referred to as PILOT2 is designed to calculate turbulent boundary layer flow for the compressible problem with pressure gradient and heat transfer in the physical plane. This program also is limited to two-dimensional flows with perfect gas thermodynamics and a Sutherland Law formulation for the viscosity.

A detailed description of the problem formulation along with the development of the working differential equations and the necessary auxiliary conditions is presented in Parts I and II of this report. This part is intended primarily to serve as a program user's manual and contains:

a. A description of the general program features and a flow diagram describing the overall logical flow of the program.

b. A detailed description of program options and their use.

c. Detailed instructions for the preparation of input data with samples for a few cases.

d. A description of built-in default options (i.e., the modes of operation or pre-set data items the program will use if it receives no other instructions to the contrary).

e. A complete description of the program built-in error messages and halts.

f. A description of the program output and some sample cases.

g. A description of each program subroutine and flow charts of some of the major program logic.

h. A description of program use, operation, accuracy, and present limitations.

i. Table of program symbols.

II. GENERAL PROGRAM FEATURES

These programs provide the user with the capability to generate the properties of a turbulent boundary layer with pressure gradient using perfect gas thermodynamics for two-dimensional flows. PILOT1, a forerunner of the compressible formulation, treated the incompressible problem only with pressure gradient and mass transfer in the physical plane. PILOT2 does the corresponding compressible flow for pressure gradient and heat transfer in physical coordinates. A Sutherland Law formulation is used to obtain the viscosity.

In PILOT1 the user may specify the conditions external to the boundary layer in terms of pressure, velocity or pressure coefficient as a function of axial distance. The wall condition inputs are blowing velocity as some other function of axial distance. All pressure, velocity and distance information input to this program is dimensional.

Conditions external to the boundary layer in PILOT2 are input with the specification of the Mach number distribution as a tabular function of normalized axial distance, the normalizing parameter being the reference length. Wall condition input information is the wall temperature distribution normalized with respect to the total temperature of the free stream or reference flow and this information is specified as a tabular function of the normalized axial distance. The normalizing parameter is, again, the reference length. These tabular functions of the axial distance need not be the same for both the Mach number and wall temperature ratio.

The user may choose to have the tabulated input information smoothed by the program before being used in the calculations. This option may be chosen independently for either external or wall conditions or both. If smoothing is chosen, the derivates of the external and wall quantities are computed from the smoothed data. In PILOT1 only velocity input information may be smoothed.

Boundary layer profiles can be calculated in PILOT1 at user specified values of axial distance, x, Reynolds number based on momentum thickness, Re_θ or local Reynolds number based on axial location, Re_x. The same capability is provided in PILOT2 except that the axial distance is a non-dimensional quantity normalized with respect to the reference length.

The user has the option of presenting PILOT2 with the input data in either English system engineering units or International (S.I.) units and requesting the output to be in either of these formats. PILOT1 has no such provision and input-output is specified in English system engineering units only.

The general flow of program computation is very similar in PILOT1 and PILOT2 and is as follows:

(a) Read in and/or evaluate all external and wall conditions, smooth them, if required, and numerically compute their derivatives.

(b) Initialize the dependent variables.

(c) In PILOT2, generate an initial value of the blowing parameter if profile information is not available.

(d) Initialize the remaining dependent variables, evaluate the wake function form selected by the user and the derivative of this function.

(e) Interpolate to find the values of the local external and wall quantities and their derivatives at the initial station.

(f) Evaluate the coefficients of the matrix of ordinary differential equations and find its solution vector.

(g) Integrate the system of equations.

(h) Calculate the boundary layer properties associated with the local solution.

(i) Store the results of a completed integration step in an output array whose size is determined by the user.

(j) Test the results of the integration to see if the program should be terminated for some reason.

(k) Check program counters to see if the results are to be printed.

(l) If printing of output information is desired, print the output according to the specific format of each program. For PILOT1 output is in four blocks which consist of:

  (1) dependent variables and their derivatives
  (2) integral properties and boundary layer parameters
  (3) external and wall properties
  (4) additional properties

  For PILOT2 the four output blocks are composed of:

  (1) dependent variables
  (2) derivatives of the dependent variables
  (3) additional properties (Group 1) - consisting of normalized axial distance, momentum and displacement thickness and Reynolds numbers based on those quantities
  (4) additional properties Group (2) - consisting of the form factor, skin friction coefficient and relative error parameters of the solution

After the output blocks are printed, the program then searches the input values of x, (or x/L), Re_θ or Re_x at which profiles are desired, to see it any are within the present bounds of the output array. If some values are within the present output array range, additional computation is performed, profiles are generated and the results are printed.

If no profile values fall within the present output array range, or if no profiles are desired, the program continues with the integration and begins to generate a new output array.

III. PROGRAM OPTIONS AND THEIR SELECTION

CARD 1 - CONTROL CARD

All program users' options for either PILOT1 or PILOT2 are selected with one control card which appears as the first member of the input data pack. In addition, this control card may be used to output the details of certain portions of the program calculation during selected steps in the computation. All selections on the control card are made in integer format and control card blanks are interpreted by the program control as zeros.

A. The following describes the option selections for PILOT1.

Columns		
1-3	NOXPTS	The number of axial points along which the external pressure, velocity or pressure coefficient will be specified. This number must be right adjusted in the first three columns on the card. At present, program dimensions are set up to handle up to and including 50 points.
4-6	NPRFPT	The number of points at which profiles are desired. This number must be right adjusted in columns 4-6. At present, provision has been made for requesting profiles at up to and including 20 values of x, Re_θ or Re_x.
7-9	NINTPT	The number of integration steps between adjacent lines of printout. Since the integration package is a variable step-size routine, this parameter provides the user with some control over the amount of computed information which is actually printed. As above, this number must be right adjusted in columns 7-9 and may be as large as 999.

Columns

10-12	KTEST	The number which determines the size of the output print blocks and must be right adjusted in columns 10-12. At present, program dimensions provide for output blocks of up to and including 50 lines. Experience with the program has indicated that a value of KTEST ≤ 50 is a good choice.
13	WAKE FUNCTION SELECTION	This column is used to select the form of the wake function desired by the user in the course of program computation. Three forms are available and are selected as follows.

If the integer in Column 13 is	The wake function form is
0	$6\eta^2 - 4\eta^3$ (after Coles)
1	$1 - \cos \pi\eta$
2	$39\eta^3 - 125\eta^4 + 183\eta^5 - 133\eta^6 + 38\eta^7$

The normal default option selects Coles wake function for evaluation.

14	MASS TRANSFER OPTION	This column permits the user to select mass transfer as an option in the program. By specifying a number other than zero in column 14, the user indicates he desires to make the program computation without mass transfer, and program control will not expect to find any such information specified. The default option, a zero or blank in column 14, indicates blowing velocity information, i.e., VBAR as a tabular function of axial distance, x, is to be expected by the program.

Columns		
15	VELOCITY SMOOTHING OPTION	If velocity information is input to the program as the specification of external conditions and the user desires to have the input information smoothed before it is used in the computation, he may insert a number other than zero in column 15. A zero or blank in column 15 results in no smoothing of input velocity information.
16	PROFILES	Column 16 is used to specify the parameter which is to serve as the independent variablve at which profiles are desired.

If the integer in Column 16 is:	Profiles will be calculated at user specified values of:
0	x
1	Re_θ
2	Re_x

(A blank in column 16 is assumed to be a zero.) If no profiles are desired (i.e., columns 4-6 are zero), column 16 is ignored. (Note: If column 16 is left blank and the program terminates via the error termination mode, a profile will be generated at the last profile point using x as the profile parameter.

17-19	NXWPTS	The number of axial points along which the mass transfer parameter will be specified, This number must be right adjusted in columns 17-19. At present program dimensions are capable of accepting up to and including 50 points.

Columns

20	EXTERNAL CONDITIONS	Column 20 is used to select the form in which external conditions are supplied to the program.

If the integer in Column 20 is:	The input option selected is:
0	Pressure as a tabular function of x
1	Velocity as a tabular function of x
2	Pressure coefficient as a tabular function of x

Note that the default option assumes the user will normally input pressure information.

21 22		Not used in this program.
23	SPECIAL HALT	Before making a lengthy computation the user might like to examine the results of the first few integration steps. By selecting a small number, n, (i.e., 2 or 3) for KTEST in column 12, inserting a 1 in column 9 for NINTPT, the number of integration steps between adjacent lines of printout, and inserting a number other than zero in column 23 the program will halt after printing an output array of n lines corresponding to n integration steps. In all other cases column 23 should be left blank.

Columns

24		Not used in this program
25	MASS TRANSFER SMOOTHING	If mass transfer information is input to the program and the user desires to have the input information smoothed before being used by the program, he may insert a number other than zero in column 25. A zero or blank in column 25 results in no smoothing of input mass transfer information.
26, 27		Not used in this program.
28	BLOCK DATA STORAGE OF QUADRATURE INTEGRATION RESULTS	The quadrature integration done by subroutine 'INTGRL' is completely independent of any other program calculations and depends only upon the form of the wake function selected by the user. To avoid the recalculation of this integral every time the program is used, the integration was performed once for the most commonly used form of the wake function, namely Coles, (i.e., $W(\eta) = 6\eta^2 - 4\eta^3$) and the results saved and pre-set in the block data subprogram. A zero or blank in column 28 indicates to program control that the user wants to use Coles form of the wake function and moreover, accepts the block data stored values. Should the user desire to use either of the other two forms of the wake function or desire to have the program recalculate the integral for Coles form of the wake function, he must insert a number other than zero in column 28.

Columns		
29	SPECIAL HALT FOR EDGE CONDITIONS	Before performing any integration the user may desire to examine the input and default data the program will actually use in the calculations as well as the wall conditions, edge conditions and particularly, the derivatives of the latter. This may be accomplished by merely inserting a number other than zero in column 29. The program will then print the above information and halt. During normal program operation, column 29 should be left blank.
30	ITEXT (Integration Package Test)	When a number other than zero is inserted in column 30, the integration package will print out a time history of the computing interval and the reasons for its variation. For normal program operating, column 30 should be left blank.
31-47	DUMP SWITCHES	The 17 switches represented by columns 31-47 may be used to examine the details of the computation being made by a particular subroutine of the program. Each switch controls one subroutine and all switches are independent of one another. If a number other than a zero or a blank is inserted in any member of this group, the important parameters and some of the quantities used to compute them will be printed each time the routine associated with them is called. These switches were originally intended to aid in debugging portions of the program and have been left intact from that time. The

Columns	
31-47 (cont'd)	user is warned that the use of these switches can generate a large quantity of output. Control is as indicated below:

Column	Subroutine Dumped	Column	Subroutine Dumped
31	MAIN	39	BOUNDE
32	FUNCT	40	DERSUB
33	PROFIL	41	BLPROP
34	PRFILE	42	INTGRL
35	COEFFS	43	INIT2
36	GETFS	44	DATPRP
37	LMDA	45	INPUT
38	GETQS	46	CHSUB
		47	TRAPIN

61-64	DUMP	These columns may be used to turn on or off the tracing sequence selected in columns 31-47 by specifying the integration steps (as integers) at which the user would like the changes to occur. Three such changes are permitted and the integration step at which each is to occur should be right adjusted in columns 61-64 for the first, 65-68 for the second, and 69-72 for the third. The on-off mechanism is keyed to the switch for MAIN (Column 31). The following example will illustrate the use of the above. The user desires to trace the routine called 'BOUNDE' for the first three integration steps, then trace the program between the 52 and 153 integration steps, and then continue the calculation in the normal mode. The switch settings would be:
65-68	SWITCH	
69-72	VALUES	

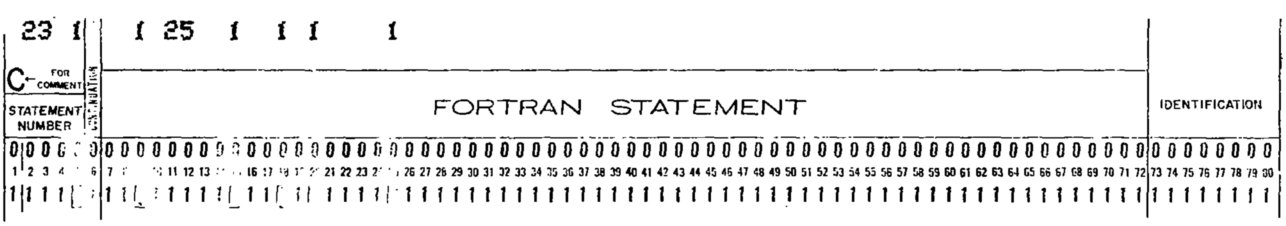
Columns

61-72 (cont'd)

Column	Integer
31	1
39	1
64	3
67	5
68	2
70	1
71	5
72	3

This would result in MAIN and BOUNDE being traced for the first three integration steps. The tracing sequence would be shut off after the third integration step and would be turned on again for all routines at integration step number 52. The tracing would continue through step 153 at which time it would be turned off and the computation would proceed normally. Note that for normal program operation columns 61-72 should be left blank.

To illustrate the preparation of the control card for PILOT1 a sample is presented below.



For this case, the user prescribes 23 points (columns 2 and 3) at which velocity information (column 20 contains a 1) is input. Profiles are to be generated at 10 points (column 5 contains a 1 and column 6 is blank (i.e., assumed to be zero)). The axial coordinate, x, is the profile parameter selected. (column 16 is left blank).

Output information will be in blocks of 25 lines (columns 11 and 12), each line representing 1 integration step (column 9).

Coles form of the wake parameter is used (column 13 is blank) as pre-set in the block data subprogram (column 28 is blank).

Mass transfer information is being input (column 14 is blank) via a table containing 10 pieces of data (columns 18 and 19).

Both velocity and mass transfer information is to be smoothed before being used (columns 15 and 25 are 1). A table of controlcard parameters is provided at the end of this report for quick reference.

B. The section that follows will now describe the option selections available for PILOT2.

Columns

1-3	NOXPTS	The number of axial points along which the Mach number will be specified. This number must be right adjusted in the first three columns on the card. At present, program dimensions are set up to handle up to and including 50 points.

Columns

4-6 NPRFPT The number of points at which profiles are desired. This number must be right adjusted in columns 4-6. At present, provision has been made for requesting profiles up to and including 20 values of $^x/L$, Re_θ or Re_x.

7-9 NINTPT The number of integrations steps between adjacent lines of printout. Since the integration package is a variable step-size routine, this parameter provides the user with some control over the amount of computed information which is actually printed. As above, this number must be right adjusted in columns 7-9 and may be as large as 999.

10-12 KTEST The number which determines the size of the output print blocks and must be right adjusted in columns 10-12. At present, program dimensions provide for output blocks of up to and including 50 lines. Experience with the program has indicated that a value of KTEST $\leq$ 50 is a good choice.

13 WAKE FUNCTION SELECTION This column is used to select the form of the wake function desired by the user in the course of program computation. Three forms are available and are selected as follows:

If the integer in column 13 is	The wake function form is
0	$6\eta^2 - 4\eta^3$ (after Coles)
1	$1 = \cos \pi\eta$
2	$39\eta^3 - 125\eta^4 + 183\eta^5 - 133\eta^6 + 38\eta^7$

The normal default option selects Coles wake function for evaluation.

Columns

14	LEADING EDGE OPTION	If profile information is not available and the user desires that the program generate an initial value of the dependent variable representing mass transfer, VBARO, from the specified initial value of the skin friction parameter, PHIO, and the other input initial conditions, he inserts a number other than zero in coluum 14. With a zero or blank in column 14, a value of VBARO must be input or the pre-set value stored in the block data subprogram will be used.
15	MACH NUMBER SMOOTHING	If the user desires to smooth the input Mach number information before it is used by the program, he inserts a number other than zero in column 15. Otherwise no smoothing on this input data is performed.
16	PROFILES	Column 16 is used to specify the parameter which is to serve as the independent variable at which profiles are desired.

If the integer in column 16 is:	Profiles will be calculated at user specified values of:
0	x/L
1	Re_θ
2	Re_x

(A blank in column 16 is assumed to be zero.) If no profiles are desired (i.e., columns 4-6 are zero) column 16 is ignored. If column 16 has been left blank and the program terminates via the error termination mode, a profile is generated with $^x/L$ as the profile parameter.

Columns		
17-19	NXWPTS	The number of axial points along which wall temperature data will be specified. This number must be right adjusted in columns 17-19. At present, program dimensions are capable of accepting up to and including 50 points.
20		Not used in this program
21		
22		
23	SPECIAL HALT	Before making a lengthy computation the user might like to examine the results of the first few integration steps. By selecting a small number, n, (i.e., 2 or 3) for KTEST in column 12, inserting a 1 in column 9 for NINTPT, the number of integration steps between adjacent lines of printout, and inserting a number other than zero in column 23 the program will halt after printing an output array of n lines corresponding to n integration steps. In all other cases column 23 should be left blank.
24		Not used.
25	WALL TEMPERATURE SMOOTHING	If the user desires to smooth the input wall temperature information before it is used by the program, he inserts a number other than zero in column 25. Otherwise, no smoothing on this input data is performed.
26-27	UNITS SELECTION	Provision has been made in the program for specifying either input, output, or both in either English system engineering units (i.e., the pound-force, slug-mass system) or the

Columns

26-27 (cont'd) International System (S.I.) which is basically the MKS system. Column 26 controls the units of the information to be input. If column 26 is other than zero, the program expects the input information to be in S.I. units. Column 27 controls the units of the information to be output. As above, if column 27 is other than zero, the program assumes the user desires the output information in S.I. units. If columns 26 and 27 are left blank, the default options (i.e., English system units are expected for input and will be used for output) are used.

Two additional items must be mentioned: (1) the units of input quantities may not be mixed between the systems, and (2) all internal calculations of dimensional quantities are performed using English system engineering units and the details of the computation of some selected portion of the program will be output in this system.

28 BLOCK DATA STORAGED QUADRATURE INTEGRATION RESULTS

The quadrature integration done by subroutine 'INTGRL' is completely independent of any other program calculations and depends only upon the form of the wake function selected by the user. To avoid the recalculation of this integral everytime the program is used, the integration was performed once for the most commonly used form of the wake function, namely Coles, (i.e., $W(\eta) = 6\eta^2 - 4\eta^3$) and the

Columns

28 (cont'd)		results saved and pre-set in the block data subprogram. A zero or blank in column 28 indicates to program control that the user wants to use Coles form of the wake function and moreover, accepts the block data stored values. Should the user desire to use either of the other two forms of the wake function or desire to have the program recalculate the integral for Coles form of the wake function, he must insert a number other than zero in column 28.
29	SPECIAL HALT FOR EDGE CONDITIONS	Before performing any integration the user may desire to examine the input and default data the program will actually use in the calculations as well as the wall conditions, edge conditions and particularly, the derivatives of the latter. This may be accomplished by merely inserting a number other than zero in column 29. The program will then print the above information and halt. During normal program operation, column 29 should be left blank.
30	ITEXT (Integration Package Test)	When a number other than zero is inserted in column 30, the integration package will print out a time history of the computing interval and the reasons for its variation. For normal program operating, column 30 should be left blank.
31-53	DUMP SWITCHES	The 23 switches represented by columns 31-53 may be used to examine the details of the computation being made by a particular subroutine of the program. Each switch controls one subroutine and all switches are independent of one

Columns

31-53 (cont'd) another. If a number other than a zero or a blank is inserted in any member of this group, the important parameters and some of the quantities used to compute them will be printed each time the routine associated with them is called. These switches were originally intended to aid in debugging portions of the program and have been left intact from that time. The user is warned that the use of these switches can generate a large quantity of output. Control is as indicated below:

Column	Subroutine Dumped	Column	Subroutine Dumped
31	MAIN	42	INTGRL
32	FUNCT	43	INIT2
33	PROFIL	44	NOT USED
34	PRFILE	45	INPUT
35	COEFFS	46	CHSUB
36	GETFS	47	TRAPIN
37	LMDA	48	SUBLYR
38	GETQS	49	PARDRV
39	BOUNDE	50	VSTART
40	DERSUB	51	NOT USED
41	BLPROP	52	UNITS
		53	FPRIM

Columns		
61-64	DUMP	These columns may be used to turn on or off the
65-68	SWITCH	tracing sequence selected in columns 31-53 by
69-72	VALUES	specifying the integration steps (as integers)

at which the user would like the changes to occur. Three such changes are permitted and the integration step at which each is to occur should be right adjusted in columns 61-64 for the first, 65-68 for the second, and 69-72 for the third. The on-off mechanism is keyed to the switch for MAIN (column 31). The following example will illustrate the use of the above. The user desires to trace the routine called SUBLYR for the first three integration steps, then trace the program between the 52 and 153 integration steps, and then continue the calculation in the normal mode. The switch settings would be:

Columns	Integer
31	1
48	1
64	3
67	5
68	2
70	1
71	5
72	3

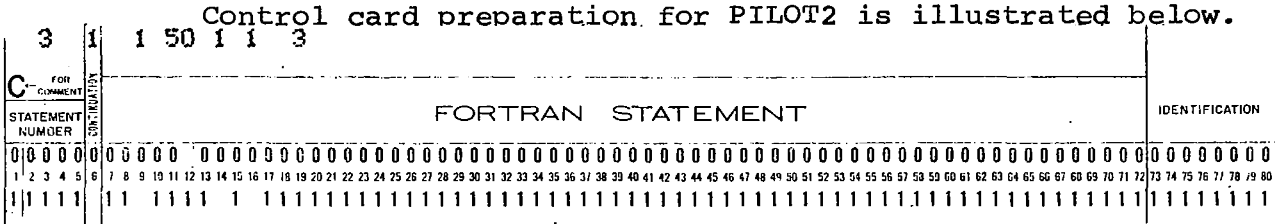
This would result in MAIN and SUBLYR being traced for the first three integration steps. The tracing sequence would be shut off after the third

Columns

61-72 (cont'd)

integration step and would be turned on again for all routines at integration step number 52. The tracing would continue through step 153 at which time it would be turned off and the computation would proceed normally. Note that for normal program operation, columns 61-72 should be left blank.

Control card preparation for PILOT2 is illustrated below.



For this case, the user prescribed the Mach number and wall temperature ratio at 3 points along the body and is asking for 1 profile at a specified value of Re_θ. He desires his output in blocks of 50 lines, each line representing 1 integration step.

In addition, he has selected Coles form of the wake function as stored in the block data subprogram and has asked the program to generate an initial value of VBAR.

No smoothing is performed on either the external or wall input conditions and all input and output is handled in English system engineering units.

IV. PREPARATION OF PROGRAM INPUT DATA

Program input follows, as closely as possible, the general format used in the forerunner of these two programs and described in detail in Reference 1.* Input data for both programs is prepared in very much the same way and is described separately below. As previously mentioned, the first card of any set of input data must be a control card and its preparation is described in Section III. This section will discuss the remaining input data and its preparation.

Information input to this program is facilitated by combining the use of two standard FORTRAN features; a) block-data storage of a large number of data items which are not changed often or which are standard for a particular input option, and b) namelist - which provides greater flexibility by (1) permitting only the information acutally required to run a given problem to be input in any order, and in any format, (2) by providing for the input of array information in a simple, compact form, and (3) by providing a permanent, easily identifiable record of the input information.

A. Input Requirements for PILOT1

Three separate categories of namelist information can be supplied to the program as input, two of which are always required. They are discussed below in the order in which they appear in the input-data pack.

OVRIDE - This namelist array is always required and is used for input of all free-stream or reference conditions, initial values of the dependent and independent variables, wall temperature, program constants, reference lengths, initial and maximum permitted integration step sizes, truncation error tolerances and points at which profiles are desired.

---

* Reference (1) Schneider, J. and Boccio, J.,"An Investigation of the High Speed Turbulent Boundary Layer with Heat Transfer and Arbitrary Pressure Gradient," Part III-Computer Program Manual, NASA CR-1681, October 1970.

Consequently, the second card of the input data pack must always begin with the following format:

```
          $  OVRIDE |  |   at least one space

Column    2  3    8  9
```

Any or all of the above-mentioned items may then be loaded beyond Column 9, free field, in any order, in any format, and in as many cards as are required to complete the input data requirements for the particular case of interest. The data is input by punching its <u>program variable name</u>, an <u>equal sign</u>, and the <u>value of that variable</u>, in any format. Each data item must be separated by a comma and no attention need be paid to spacing between data items, between the variable name and equal sign or between the equal sign and the actual value of the parameter.

A few additional simple rules must be observed.

1. all data continuation cards must start in column 3 or beyond,
2. no unnecessary blanks are permitted in the middle of an input number,
3. the last item on each card, except for the last item on the last card, must be a comma,
4. input must be terminated by a $ somewhere after the last data item.

A sample of a typical program input is shown below:

CARD 2

```
$OVRIDE UEO =53.68,REQLO =.3399E+6,PREF =14.79,RHOEO =0.00226732,
```

C ← FOR COMMENT | STATEMENT NUMBER | CONTINUATION | FORTRAN STATEMENT | IDENTIFICATION

CARD 3

```
THWALL =540.,UEBARO =1.,BETA=0.018,X0=0.4631,CHIBAR= 0.,CHIMAX =1.E8,
```

CARD 4

```
DCIMAX=0.5E5,PIO=0.185844,PHIBRO=22.3607,VTLDAO=0.00182,
```

CARD 5

```
DCHIBR=5000.,
```

CARD 6

```
XPROFL(1)=0.4664,0.6913,0.9579,1.2078,1.4494,1.7909,2.0825,2.3657,
```

CARD 7

```
2.5823,2.8488$
```

Note that cards 3, 4, 5 and 6 could have been shuffled in any order with no change in the input data received by the program.

The following list of variables may be input to the program via OVRIDE. Only the first group of 9 must always be specified. Values for the remaining are either calculated or are stored in block data. These latter may be changed, if desired, by merely including the desired values anywhere on the OVRIDE input cards before the last $. (Note: <u>no numeric zeros are ever used in any variable name in this program</u>.) For a complete description of all program symbols the user is referred to the table of symbols at the end of this report.

These are required input in OVRIDE:

UEO	-	the free stream or reference velocity - ft/sec
PREF	-	the free-stream or reference static pressure - lbf/in^2
REQLO	-	the free-stream or reference Reynolds number per unit length - ft^{-1}
PIO	-	initial value of the Coles wake parameter - dimensionless
PHIBRO	-	initial value of the skin-friction parameter - dimensionless
TWALL	-	the wall temperature - ^{o}R
RHOEO	-	the free-stream or reference density - $slugs/ft^3$
UEBARO	-	the normalized initial value of axial velocity
VBARO	-	the normalized initial value of the mass transfer parameter

Input of these is at the choice of the user	CAY1 CAY2 BETA ETASTR	Non-dimensional program constants preset in block data. See the table of symbols for definitions.
	XO LREF	Reference dimensions preset in block data - ft.
	DCHIBR CHIMAX PHIMAX DCIMAX ELE1 ELE2 ELT	Integration package parameters (i.e., step sizes, cut-off points, truncation error tolerances) preset in block data. See symbols table for their definitions.

CHIBAR	-	initial value of the independent variable.
ORDRAY	-	array of orders of interpolation preset in block data.
XPROFL	-	points at which profiles are desired - dimensional with units of ft. only if X is the specified profile parameter.

PRESSR/SPEED/PCOEFF - One of these namelist names is always required and follows immediately after OVRIDE. The one to be used depends upon the selection made in column 20 on the control card. In any case, 50 values of the XE and either PE, UEIN or CP, the external pressure, velocity or pressure coefficient, respectively, may be input. A sample of the input is presented below:

```
$SPEED XE(1)=0.4631,0.5622,0.6722,0.7913,0.9004,1.0045,1.1145,1.2186,
  1.3228,1.4369,1.5460,1.6560,1.7751,1.8742,2.0,2.0933,2.2232,2.3049,
  2.3998,2.5306,2.6347,2.7439,2.8480,
 UEIN(1)=53.68,54.753,54.914,55.022,55.075,54.914,54.646,54.324,
         53.68,53.196,52.606,51.962,51.318,50.942,50.566,50.137,
         49.654,49.170,48.902,48.526,48.526,48.097,47.667$
```

In this case, the control card would show

Column 20 ---- 1 (velocity input selected)

2 ---- 2

3 ---- 3 for 23 tabular points input

The program would then expect to be given 23 sets of external conditions in terms of the velocity as shown above. The one-dimensional arrays of information which represent the coordinate XE, and the velocity, UEIN, are loaded sequentially by merely identifying the array position of the first member of the group. Any repetitive information may be handled using a repetition factor (an integer and a multiplication sign) as it would be in a data statement or in standard FORTRAN arithmetic. Note that the UEIN array could have appeared before the XE array.

If external pressure or pressure coefficient had been the input choice, column 20 would have been set to 0 or 2, respectively; the namelist name used would have been PRESSR or PCOEFF, respectively, (e.g., $ PRESSR XE(1) = 0., 1.0, etc.) and in place of 23 values of the velocity there would have appeared 23 values of the pressure, PE(1) = n_1, ... n_{23} $ or 23 values of the pressure coefficient CP(1) = m_1, ... m_{23} $.

The only variables which can be input with PRESSR, SPEED or PCOEFF are:

XE - the running coordinate along the body in ft. and one of the following:

PE - the external pressure distribution - lbs/in^2

UEIN - the external velocity distribution - ft/sec

CP - the external pressure coefficient distribution - dimensionless.

The remaining namelist array is Blow 1 and is required, respectively, only when the user desires to use the mass transfer option in the program.

If BLOW1 is used (i.e., column 14 is set to zero or left blank) the input data associated with it is read immediately after the PRESSR, SPEED or PCOEFF input data is read. A sample of this input is presented below:

```
$BLOW1 XW(1)=0.4664,0.6913,0.9579,1.2078,1.4494,1.7909,2.0825,2.3657,
2.5823,2.8488,
VBAR(N(1)=0.00182,0.001822,0.001824,0.001822,0.001819,0.001817,
0.001819,0.001821,0.001821,0.001816$
```

In this case, the control card would show:

Column	18	1	for 10 tabular points input
	19	0	
	14	0	- mass transfer option selected

The program could then expect to be given 10 sets of mass transfer parameters as shown above. Note that the coordinate which specifies axial location for mass transfer information need not be the same as that used to specify the external conditions.

The only variables which can be input with BLOW 1 are:

XW - the running coordinate along the body - in ft.

VBARIN - the mass transfer parameter.

The last items of the input data pack are three cards which may be used for case identification. Up to 80 hollerith characters may be punched on each card and their contents are printed on the first page of the output. If less than three cards are required for identification purposes, blank cards must be inserted to make up the difference.

B. Input Requirements for PILOT 2

Again, as in PILOT1, three separate categories of namelist information make up the input data pack. In PILOT2, however, all are required. In addition, effort has been made in PILOT2 to keep all input information in normalized form wherever possible.

OVRIDE - This namelist array serves exactly the same function in PILOT2 that it did in PILOT1 but includes some additional parameters and renames some others. The following list of variables may be input to PILOT2 via OVRIDE. Those quantities which are always required are denoted separately as before:

These are always required input to OVRIDE:

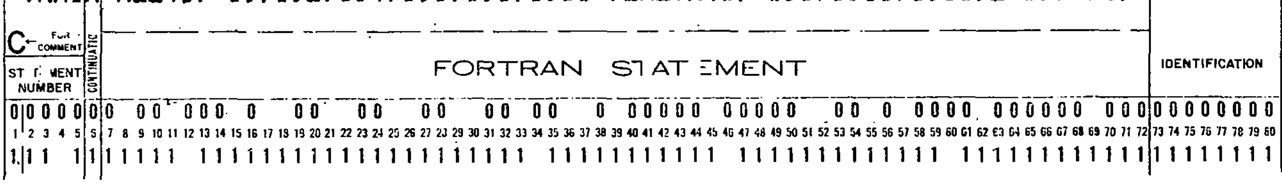
REQLO	-	the initial free-stream or reference Reynolds Number per unit length - ft^{-1} or $meters^{-1}$
TTE	-	the free-stream or reference total at the initial station temperature - ^oR or ^oK.
EMEO	-	the free-stream Mach Number.
TWALLO	-	the wall temperature at the initial station - ^oR or ^oK.

Input of these is at the choice of the user.

LREF, XOL	reference dimensions preset in block data.
PIO, PHIO, UEBARO, ETLDAO, VBARO, CHIBARO, CHIO	initial values of the dependent and independent variables preset in block data.
CAY1, CAY2, CAY3, CAY3, CAY5, BETA ETASTR, GAMA	non-dimensional program constants preset in block data.
PHIMAX, CHIMAX, DCIMAX, DCHIBRO, VPMIN, ELT, ELE1, ELE2	integration package parameters (i.e., initial and maximum step sizes, truncation error tolerances) and program cut-off test quantities - all preset in block data.
ORDRAY -	array containing the orders of the interpolation preset in block data.
XPROFL -	points at which profiles are desired - all non-dimensional.

MACH - this namelist array supplies external conditions to PILOT2 in the form of the external Mach Number, EMEIN, as a tabular function of normalized axial distance, XEL (normalized with respect to LREF). Up to and including 50 pairs of the above may be input via MACH; a sample is shown below:

```
$MACH XEL(1)=0.,0.2,0.4,0.6,0.8,1.00 ,EMEIN(1)=3.0,3.08,3.15,2*3.25,4.$
```



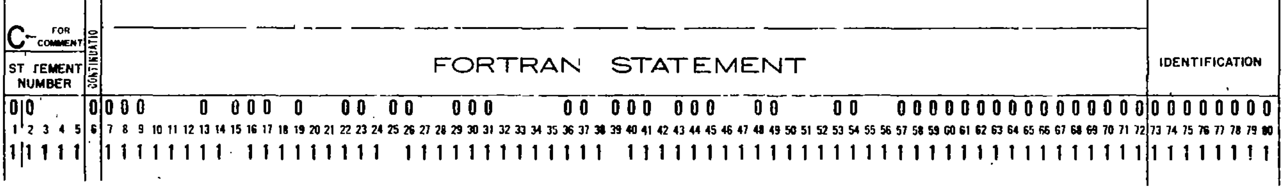
In this case the control card would show:

Column 3 6 - for 6 tabular points input.

The program would then expect to find 6 sets of external conditions to be input as shown above. Note: only XEL and EMEIN may be input with namelist MACH.

TWTABL - this namelist array supplies wall conditions to PILOT2 in the form of the wall-to-free stream total temperature ratio, TWTTEN, as a tabular function of normalized axial distance, XTWL, again normalized with respect to LREF. As before, up to and including 50 pairs of data may be input. A sample is shown below:

```
$TWTABL XTWL(1)=0.,0.5,1.0,    TWTTEN(1)=0.45,0.50,0.60,$
```



In this case, the control card would indicate:

Column 19   3 - for the 3 tabular points input.

The program would then expect to find 3 sets of wall conditions to be input as shown above. Note: only XTWL and TWTTEN may be input via namelist TWTABL. The user should also note that TWTTEN and EMEIN may be different functions of axial distance (i.e., the axial coordinates may be specified by a different number of points and a different function for each).

Input for PILOT2 is terminated in exactly the same manner as PILOT1, i.e., with three cards which may be used for case identification. Their format is exactly as indicated for PILOT1.

CONTROL CARD TABLE - PILOT1

COLUMN			IDENTIFICATION
1		No. of 100's	No. of external condition pts. which are to be input
2	NOXPTS	No. of 10's	
3		No. of 1's	
4		No. of 100's	No. of pts. at which profiles are desired
5	NPRFPT	No. of 10's	
6		No. of 1's	
7		No. of 100's	No. of integration steps between adjacent lines of printout
8	NINTPT	No. of 10's	
9		No. of 1's	
10		No. of 100's	No. of lines of printout in each print block
11	KTEST	No. of 10's	
12		No. of 1's	
13	0 - Wake parameter 1 - selection 2 - with mass	- $6\eta^2-4\eta^3$ - $1 \cos \pi\eta$ - $39\eta^3-125\eta^2$	(COLES) etc.
14	0 - transfer 1 - no mass transfer		
15	0 - no smoothing 1 - with smoothing		(VBARIN)
16	0 - Profiles at specified x 1 - " " " 2 - " " "	Re_θ Re_x	
17		No. of 100's	No. of mass transfer data which are input
18	NXWPTS	No. of 10's	
19		No. of 1's	
20	0 - Pe(x) 1 - UEIN(X) 2 - CP(X)		External Condition Option
21	Not used in		
22	this program		

COLUMN	IDENTIFICATION
23	0 - Default - Do nothing 1 - Stop after printing a short block of size KTEST
24	Not used in this program
25	0 - no smoothing 1 - with smoothing (UEIN)
26	Not used in
27	this program
28	0 - Bypass 'INTGRL' - Use block data values of INT 1 - Calculate INT via sub.INTGRL
29	0 - Do nothing 1 - Stop after printing edge condition information
30	0 - ITEXT = 0 Do nothing 1 - ITEXT = 1 - Trace reasons for size changes
31	Dump Switch for MAIN
32	Dump Switch for FUNCT
33	Dump Switch for PROFIL
34	Dump Switch for PRFILE
35	Dump Switch for COEFFS
36	Dump Switch for GETFS
37	Dump Switch for LMDA

COLUMN		IDENTIFICATION
38	Dump Switch for GETQS	
39	Dump Switch for BOUNDE	
40	Dump Switch for DERSUB	
41	Dump Switch for BLPROP	
42	Dump Switch for INTGRL	
43	Dump Switch for INIT2	
44	Dump Switch for DATPRP	
45	Dump Switch for INPUT	
46	Dump Switch for CHSUB	
47	Dump Switch for TRAPIN	
48–53	NOT USED IN THIS PROGRAM	
54–60	NOT USED IN THIS PROGRAM	
61	No. of 1000's	First integration step at which trace sequence is to change
62	No. of 100's	
63	No. of 10's	
64	No. of 1's	
65	No. of 1000's	Second integration step at which trace sequence is to change
66	No. of 100's	
67	No. of 10's	
68	No. of 1's	
69	No. of 100's	Third integration step at which trace sequence is to change
70	No. of 100's	
71	No. of 10's	
72	No. of 1's	

CONTROL CARD TABLE - PILOT 2

COLUMN	IDENTIFICATION		
1		No. of 100's	No. of Mach No. pts. which are to be input
2	NOXPTS	No. of 10's	
3		No. of 1's	
4		No. of 100's	No. of pts. at which profiles are desired
5	NPRFPT	No. of 10's	
6		No. of 1's	
7		No. of 100's	No. of integration steps between adjacent lines of printout
8	NINTPT	No. of 10's	
9		No. of 1's	
10		No. of 100's	No. of lines of printout in each print block
11	KTEST	No. of 10's	
12		No. of 1's	
13	0, 1, 2	Wake Parameter Selection	0 - $6\eta^2 - 4\eta^3$ 1 - $1 - \cos \pi\eta$ 2 - $39\eta^3 - 125\eta^4$ etc.
14	0 - VBARO is input 1 - Leading edge problem - VBARO calculated internally		
15	0- No smoothing 1 - With Smoothing	(EMEIN)	
16	0 - Profiles at specified x/L 1 - Profiles at specified Re_θ 2 - Profiles at specified Re_x		
17		No. of 100's	No. of wall temp. ratio data pts. which are input
18	NXWPTS	No. of 10's	
19		No. of 1's	
20, 21, 22	Not Used in this Program		

COLUMN	IDENTIFICATION	
23	0 - Do nothing (default) 1 - Stop after printing a short block	
24	Not used	
25	0 - No smoothing (TWTTEN) 1 - With Smoothing	
26	0 - English-System Units 1 - S. I. Units	(INPUT)
27	0 - English System Units 1 - S. I. Units	(OUTPUT)
28	0 - Bypass 'INTGRL' - Use Block Data values of INT 1 - Calculate INT via Subr. INTGRL	
29	0 - Do nothing 1 - Stop after printing edge condition information	
30	0 - ITEXT = 0 Do nothing 1 - ITEXT = 1 Trace reasons for step size changes	
31	Dump switch for MAIN	
32	Dump switch for FUNCT	
33	Dump switch for PROFIL	
34	Dump switch for PRFILE	
35	Dump switch for COEFFS	
36	Dump switch for GETFS	
37	Dump switch for LMDA	

COLUMN	IDENTIFICATION	
38	Dump switch for GETQS	
39	Dump switch for BOUNDE	
40	Dump switch for DERSUB	
41	Dump switch for BLPROP	
42	Dump switch for INTGRL	
43	Dump switch for INIT2	
44	Dump switch for Not Used	
45	Dump switch for INPUT	
46	Dump switch for CHSUB	
47	Dump switch for TRAPIN	
48	Dump switch for SUBLYR	
49	Dump switch for PARDRV	
50	Dump switch for VSTART	
51	Dump switch for Not Used	
52	Dump switch for UNITS	
53	Dump switch for FPRIM	
54, 55, 56, 57, 58, 59, 60	Not Used in This Program	
61	No. of 1000's	First integration step at which trace sequence is to change
62	No. of 100's	
63	No. of 10's	
64	No. of 1's	
65	No. of 1000's	Second integration step at which trace sequence is to change
66	No. of 100's	
67	No. of 10's	
68	No. of 1's	
69	No. of 1000's	Third integration step at which trace sequence is to change
70	No. of 100's	
71	No. of 10's	
72	No. of 1's	

V. PRE-SET DEFAULT DATA

Both the PILOT1 and PILOT2 programs, like their predecessors of Reference 1, contain stored data which have been pre-set at compilation time. These data include program constants, test parameters against which program computed quantities are continually being tested, truncation error tolerances used for the dependent variables during integration and initial values for the dependent and independent variables and reference dimensions which are helpful in preparing program input particularly when multiple cases are to be run.

Since the block data subprogram is slightly different for PILOT1 and PILOT2 this section of the manual has also been separated into two parts which describe the contents of block data for each program.

A. BLOCK DATA SUBPROGRAM - PILOT1

The first group of these data are dimensionless constants some of which are typical of turbulent flows.

CAY1	= 0.4115	constants associated with the zero mass transfer case in the equation for the law-of-the-wall
CAY2	= 4.90	
BETA	= .018	a parameter used in the description of the incompressible eddy viscosity
ETASTR	= 0.5	a percentage value of the incompressible boundary layer height where the Clauser eddy-viscosity model is assumed to apply
PIE	= 3.14159	the universal constant
DBDVTW	= 0.25	the constant value of the derivative of $\beta(\tilde{v}_w)$ used in the working form of the velocity profile relationship

The next group of pre-set information contains test parameters against which program computed quantities are being compared. These are:

PHIMAX	$= 10^3$	the maximum permitted value of the skin friction parameter. Should this value be exceeded, the program prints an error message, prints the contents of the output array, and any profiles which have been requested, and then proceeds to the next case.
CHIMAX	$= 10^8$	The maximum permitted value of the stream-wise Reynolds number. Should this value be reached in the course of the computation, the output array is printed, any profiles requested up to that point are printed and the program prints a message indicating case completion. The program then returns to the input section and tests to see if data for another case is present.
VPMIN	$= .0001$	as the blowing goes to zero (i.e., $\left\| \tilde{v}_w \right\| \rightarrow 0$, certain of the equations used in the computation become indeterminate. One may, in general, find their limiting forms by the application of L'Hôpitals Rule. These limiting forms of the relationships are included in the program and are used in the calculation when the blowing as determined by $\left\| \tilde{v}_w \cdot \varphi^2 \right\|$ goes below this arbitrary cutoff value, VPMIN.

DCIMAX = 10^7 the absolute value of the maximum step size that the integrator is permitted to use.

The next group of stored data consists of integration package tolerances and parameters and orders of the interpolations.

ELE1 = the one-dimensional array of 3 values, one corresponding to each of the 3 dependent variables, which is the upper bound of the local relative truncation error for the respective dependent variables. If the error for any variable exceeds its respective ELE1 value, the computing interval is halved and the integration restarted at the beginning of the present interval. If the error for all the variables is less than 1/128 of their respective ELE1 values, the computing interval is doubled for the next integration step. The pre-set values of the ELE1 array are shown below.

ELE2 = the one-dimensional array of 3 values which represent a "relative zero" for the respective dependent variable. If the absolute value of any of the dependent variables is less than its respective ELE2 value, the relative error criterion for the variable will not be applied. The pre-set values for the ELE2 array are also shown below.

ELT = A one dimensional array of values supplied by the user and used by the integrator to return control to the main program during the course of the integration. This mode of control is not used in this program.

DEPENDENT VARIABLES	ELE1 MEMBER	VALUE	ELE2 MEMBER	VALUE
PHI (φ)	(1)	1.0×10^{-4}	(1)	1.0×10^{-9}
RBAR ($\bar{R}$)	(2)	1.0×10^{-4}	(2)	1.0×10^{-9}
PI (π)	(3)	1.0×10^{-4}	(3)	1.0×10^{-9}

NINTPT = A user input which specifies the number of integration steps between adjacent lines of print out the user desires. Unless changed, NINTPT is set to 1, i.e., every integration step is printed.

ORDRAY = The 16 element array which contains values for the orders of interpolation which are performed in various portions of the program. Only the first eight of these are used in PILOT1. Their values and the routines they are used in are tabulated below.

ORDRAY ELEMENT NO.	VALUE	ROUTINE WHICH USES IT	WHAT IS BEING COMPUTED & INTERPOLATED
1	2	LAGDER	in'DATPRP'(DVWDX)
2	2	LAGDER	in'DATPRP'(DPEDX)
3	2	LAGDER	in'DATPRP'(DUEDX)
4	2*	LGRANG	in'BOUNDE'(FETCH1)
5	1	LAGR ;	in'GETFS'(WESTR)
6	2*	LGRANG	in'PRFILE'(ANSRX)
7	1	LAGR	in'FUNCT'(ETA)
8	2*	LGRANG	in'BOUNDE'(FETCH2)

* NOTE: LGRANG requires the number of points used in the interpolation (i.e., the order + 1) rather than the order.

The next group of pre-set data contains all the initializing information.

DCHIBR	=	500.	the initial integration step size for the independent variable CHIBAR.
CHIBAR	=	0.	the independent variable used in the integration.
XO	=	0.ft.	the initial value of the axial coordinate.
LREF	=	1.ft.	the reference length.
VBAR, DVWDX	=	0.	the values of the blowing in the physical plane are all pre-set to zero as are their derivatives.
YSPLSI	=	10.6	the value of the incompressible Reynolds number based upon shear velocity and sublayer height.

The last item in the block data subprogram is the contents of the 3-dimensional array which stores the results of the quadrature integration of

$$\mathrm{INT}(\eta,P,Q) = \int_0^{\eta} \left[w(\eta)\right]^P \left[\ell n\ \eta\right]^Q d\eta \quad ; \quad \eta = .5,\ 1.$$

This integral is computed using Coles Wake Law, i.e.,

$$w(\eta) = 6\eta^2 - 4\eta^3$$

The program uses these results in the course of the computation for evaluating the coefficient of the matrix of ordinary differential equations unless otherwise requested to do so by the user.

B. BLOCK DATA SUBPROGRAM - PILOT2

This first group of pre-set constants is identical to those of PILOT1 with some additions.

CAY 1	= 0.4115	zero mass transfer constants
CAY 2	= 4.90	in the law of the wall relation.
CAY 3	= 198.6	constants associated with the form
CAY 4	= 331.	of Sutherland's Law used in this
CAY 5	= 397.2	program.

The remaining constants in this group are identical to those of PILOT1.

BETA = .018 , PIE = 3.14159

ETASTR = 0.5 , DBDVTW = 0.25

The next group, which contains the pre-set values of the test parameters against which program generated quantities are being compared is identical to that of PILOT1 and is:

PHIMAX = 10^3 , CHIMAX = 10^8

VPMIN = .0001 , DCIMAX = 10^7

The next group in PILOT2 contain integrating parameters and integration tolerances and orders of interpolation. These are:

ELE1 = ELE2 — these one-dimensional arrays now contain 8 values corresponding to the 8 dependent variables in PILOT2

The table of these is shown below:

DEPENDENT VARIABLE	ELE1 MEMBER	VALUE	ELE2 MEMBER	VALUE
RBAR($\bar{R}$)	(1)	1.0×10^{-4}	(1)	1.0×10^{-9}
PHI(φ)	(2)	↓	(2)	↓
PI(π)	(3)	↓	(3)	↓
UEBAR($\bar{u}_e$)	(4)	↓	(4)	↓
VBAR($\bar{V}$)	(5)	↓	(5)	↓
STILDA($\tilde{\sigma}$)	(6)	↓	(6)	↓
ETILDA ($\tilde{\eta}$)	(7)	↓	(7)	↓
CHI(χ)	(8)	↓	(8)	↓

As in PILOT1, the ELT array is not used in this program. NINTPT as in PILOT1 is set to 1 unless changed by the user.

ORDRAY = 10 elements of this 16 element array are assigned for use in PILOT2 to transmit instructions to the interpolating routines: where possible the array elements have been maintained consistent with their use in PILOT1. The values and usage are tabulated below.

ORDRAY ELEMENT NO.	VALUE	ROUTINE WHICH USES IT	WHAT IS BEING COMPUTED & INTERPOLATED
(1)	2	LAGDER	by 'INPUT'(DMEDX)
(2)	2	LAGDER	by 'INPUT'(DTWDX)
(3)	2	NOT USED	
(4)	2*	LGRANG	by 'BDUNDE'(FETCH1)
(5)	1	LAGR	by 'GETFS'(WESTR)
(6)	2*	LGRANG	by 'PRFILE'(ANSRX)
(7)	1	LAGR	by 'FUNCT'(ETA)
(8)	2*	LGRANG	by 'BUNDE'(FETCH2)
(9)	1	LAGR	by 'INIT2'(EME)
(10)	1	LAGR	by 'INIT2'(TWTTE)

* NOTE: LGRANG requires the number of points used in the interpolation rather than the order.

The next group of data contains the initializing information and is composed of:

LREF	= 1. ft.	the reference length
XOL	= 0.	normalized initial location for the start of the calculation
DCHIBRO	= 500.	the initial step size in CHIBAR used by the integrator
CHIBARO	= 0.	the initial value of the independent variable
YSPLUS	= 10.6	the value of the incompressible Reynolds number based on shear velocity and sub-layer height and used as an initial guess for computing YSPLUS
UEBARO	= 1.0	initial values of the dependent variables used unless otherwise specified
ETLDAO	= 1.0	
PHIO	= 15.0	
PIO	= 0.6	
CHIO	= 0.	

The last item in the BLOCK DATA Subprogram of PILOT2 is the same as that in PILOT1, i.e., the contents of the three-dimensional array which stores the result of the quadrature integration for INT(P,Q,R). A summary of this pre-set information for PILOT1 and PILOT2 is presented for easy reference at the end of this report.

VI. ERROR MESSAGES

These programs have been constructed in a manner similiar to their predecessor described in detail in Reference 1, i.e., each has a subroutine called "ERROR" which prints a message to the user should trouble develop in the normal course of a computation. These messages are designed to be as informative as possible and indicate

a) an error number which corresponds to an error message described in this section

b) what subroutine called the error routine

c) the current numerical value of one or two key program variables involved in the computation.

"Error" may be called by any program routine and has its own set of program termination logic.

All error messages in PILOT1 and PILOT2 are fatal, i.e., the present calculation is terminated. The termination procedure is as follows:

a) Subroutine "OUTPUT" is called and prints the present contents of the output array. This array will contain the results of all the calculations for all the integration steps since the last printed block.

b) Subroutine "PRFILE" is called. This routine is the first of the profile-generating sequence of routines and checks to see if any of the points at which profiles may have been requested lie within the present output array range. If any points are in the table range, profiles for these remaining points are generated along with profiles at the very last complete integration step, and all are printed. The program is then directed to return to subroutine "MAIN" where internal program switches are reset and new input data are sought.

The following text describes the error messages, indicates whether they are common to both PILOT1 and PILOT2, indicates the routines which call them and describes the information they contain:

ERROR NUMBER	DESCRIPTION
50	Called from subroutine 'MAIN'. This error has occurred in the integration package, subroutine 'INT1A'. 'ERROR' prints the integration package error indicator, IERR which indicates a) that the ELT table was not monotonic (IERR = 2) b) that truncation error problems have developed in INT1A (IERR = 3 or 4) In addition, 'ERROR' prints the last value of the independent variable CHIBAR, to indicate to the user how far the computation had progressed before trouble developed. The program then terminates as described above. This error message is common to both PILOT1 and PILOT2.
51	Called from subroutine 'MAIN'. The skin friction parameter, $\bar{\varphi}$, has exceeded the maximum value permitted, i.e., PHI > PHIMAX. (Unless otherwise changed by the user, the pre-stored value for PHIMAX = 1000.) The ERROR routine prints the last computed value for PHI and the last value of the integration step counter, IINTRL. The program then terminates in the standard mode. This error message is also common to both PILOT1 and PILOT2 .

ERROR NUMBER	DESCRIPTION
52	This error message is called from subroutine 'INPUT' in both PILOT1 and PILOT2, and is generated by the data smoothing routine called 'SMOOTH'. It always results from supplying the data smoothing routine with too few points (i.e., the minimum number is 3) for the least-square calculation. ERROR prints the value of the number of points input to 'SMOOTH', NXWPTS, then terminates the calculation. Note that in PILOT1 NXWPTS represents the number of points input to the table of VBAR vs XW since the mass addition is a physical input. In PILOT2, since mass addition is not done in the physical plane, NXWPTS represents the number of points input to the table of wall temperature versus x, i.e., TWTTEN vs XTWL.
53	This error message is also generated by subroutine 'SMOOTH' but is called from the data preparation routine, DATPRP, in PILOT1 and from 'INPUT' in PILOT2. As above, it always results from supplying the smoothing routine, with less than 3 points for its least-square computation. In this case, 'ERROR' prints the value of NOXPTS, the number of points input to 'SMOOTH' and then terminates the calculation. In PILOT1 NOXPTS represents the number of input points to the external velocity table, UEIN vs XE, while in PILOT2. NOXPTS signifies the number of external Mach number points which have been input, i.e., EMEIN vs XEL.

ERROR NUMBER	DESCRIPTION
54	This error message is called from subroutine 'INTGRL' and is generated by the service routine which performs quadrature integration, 'TRAPIN'. In this case, 'TRAPIN' is called upon to evaluate the integral, INT(ETA, P, Q) = $\int_0^{\eta}[W(\eta)]^P[\ln\eta]^Q d\eta$ by quadratures using the trapezoidal rule. If, in the attempt to perform this integration to within a relative error of .0001, 50 iterations are exceeded, ERROR prints a message to that effect along with the last value of the integral and the number of iterations performed. The program then terminates in the standard mode. This error is common to both PILOT1 and PILOT2.
55	This error message is called from 'DERSUB', the routine which calculates the derivatives used by the integration package, 'INT1A', and is common to both PILOT1 and PILOT2. The message indicates that the matrix of coefficients of the differential equations which has been presented to the service routine 'SIMQ' for inversion is singular. The error routine prints the values of the skin friction parameter, PHI and the value of the integration step counter IINTRL. Error then prints the contents of the coefficient array and the solution vector before inversion was attempted. The calculation is then terminated in the standard error mode.

ERROR NUMBER	DESCRIPTION
56	Called from 'GETFS'; - this error message is generated in the interpolating service routine, LAGR, which has tried to find the quantity, WESTR, $W(\eta^*)$ corresponding to ETA equal to ETASTR ($\eta = \eta^*$) from a table of WETA vs ETARAY (W vs η) by Lagrangian interpolation and has failed. 'ERROR' prints the last value of the answer from 'LAGR' and the error indicator KE which is either 1, 2, or 3 depending upon whether the argument was below the lowest table value, above the largest table value or the number of points were insufficient for interpolation, respectively. The program then terminates in the prescribed manner. This error message is also common to both PILOT1 and PILOT2.
57	This message is called from the function subprogram 'FUNCT' and is generated by 'LAGR' in attempting to find a value of $W(\eta)$ with a given argument from a table of WETA versus ETARAY $\left[W(\eta) \text{ vs } \eta\right]$ by Lagrangian interpolation. The interpolation routine is called in this instance in connection with finding the integral INT(ETA, P, Q) $= \int_0^{\eta} \left[W(\eta)\right]^P \left[\ln \eta\right]^Q d\eta$ by quadratures. As above, ERROR prints the last value of the answer from 'LAGR' and the error indicator, KE. Also, as above, the program is then terminated. This error message is again common to PILOT1 and PILOT2.

ERROR NUMBER	DESCRIPTION
58	This error message is called from 'GETYSP' and is contained in both PILOT1 and PILOT2. If the above routine cannot converge to a value of YSPLUS (Y_s^+) for the given value of VWPLUS (V_w^+) within 20 iterations, ERROR is called and prints out a message to that effect. In addition, 'ERROR' prints out the last iterate for YSPLUS and the input value of VWPLUS, the latter in integer format multiplied by 10,000. The program then terminates in the standard error mode.

<u>The following 4 error messages are contained only in PILOT2</u>

59	This error message is called from 'INIT2' and is generated by subroutine 'LAGR' in attempting to find a value of the external Mach number, EMEI, for the given initial value of normalized length, XOL, from a table of external Mach number versus normalized length, EME vs XEL, by La Grangian interpolation. When the interpolation is unsuccessful, ERROR is called and prints the last value of the answer and the error indicator, KE. The program is then terminated.
60	This error message is identical to error message 59 and is also called from 'INIT2'. It is associated, however, with interpolation of the wall temperature ratio table, TWTTE vs XTWL, for the given initial value of normalized length, XOL. If any trouble develops in obtaining an interpolated value, WBARI, ERROR writes out the error message of error 59 but designates it as error #60. The program then terminates as above.

ERROR NUMBER	DESCRIPTION
61	Called from 'GETFS'; - If, in the course of computing F(ETA), [F(η)], the quantity $(PHI)^3 \cdot$ VBAR/UEBAR becomes less than or equal to -1, an imaginary solution would result if the calculation were allowed to proceed further. To prevent this, ERROR is called and writes a message indicating the above has occurred. Error then writes out the current values of VBAR($\bar{V}$) and PHI(φ), the latter in integer format multiplied by 10,000 and then terminates the calculation.
62	Called from 'VSTART'; - the Newton-Raphson iteration technique used to determine USTLDAO ($\tilde{U}_{s_o}$) from the initial values of the external and wall conditions and the initial value of the skin friction parameter, PHIO, (φ_o) has not converged in 100 iterations to within a tolerance of .001. ERROR prints the initial guess for the root, USTLDAO, and the error indicator, KE. The program then terminates in the standard error mode.

VII. PROGRAM OUTPUT

This section describes the format of the program output for both PILOT1 and PILOT2 for the various program options that may be selected, defines the notation used in the output format and presents some samples of the output for illustration.

The first page of output specifies the system of units that will be used for all output quantities (note: a different system of units may have been selected for input in PILOT2) and the major options that have been chosen. In addition, the identifying information which has been punched on the three comment cards used to terminate the input data for each case, are printed.

The second page prints the values of the input and computed free stream or reference conditions. In PILOT1, these are the velocity, static pressure, density, Reynolds number per unit length, stagnation pressure and reference length. In PILOT2 they are Mach number, total temperature, Reynolds number per unit length, reference length and normalized initial length. In addition, the program prints the particular variable name (x, Re_θ, or Re_x) that has been chosen for profile generation, and the values of that variable at which profiles will be printed. If no profiles are requested, a message to that effect is also printed. The last item on this page is a printout of the control card indicators that have been selected.

The next page is a printout of namelist OVRIDE and contains:

a) all the values of the quantities that have been selected by the user along with

b) all the default options and pre-set data that the program will use in the course of the computation.

The following one or two pages contain all the wall and edge condition information which has been input or generated by the initialization portions of the program, output in a variable namelist-type format. These quantities are printed with their program variable names and are, in the order in which they are printed:

(A) IN PILOT1 XE (ft)	the axial coordinate along the body at which external pressure, velocity or pressure coefficient distributions are prescribed.
PE (lb/ft^2) DPEDX $(lbf/ft^2/ft)$	the external pressure distribution and its derivative w.r.t. axial distance, respectively
CP	pressure coefficient distribution
UE(ft/sec) DUEDX(ft/sec/ft)	the working external velocity distribution and its derivative w.r.t. axial distance, respectively
UEIN(ft/sec)	the input external velocity distribution (note: if no smoothing is needed, UE and UEIN will be identical. Velocity derivatives are always calculated from UE.)
XW(ft)	the axial coordinate along the body at which the mass transfer distributions are prescribed
VBARIN	the normalized input mass transfer distribution

VBAR DVWDX	The working mass transfer distribution and its derivative w.r.t. axial distance, respectively (again, if no smoothing is used, VBAR and VBARIN are identical. DVWDX is always computed based on VBAR).

B. IN PILOT2

Note: All quantities below have been normalized w.r.t. the reference length and/or the reference total temperature.

XEL	the normalized axial coordinate along which the external Mach number is specified
EMEIN EME DMEDX	the input external Mach number, the working value of this Mach number and its derivative w.r.t. normalized axial distance, respectively, as above, EME and EMEIN are identical if no smoothing is used and DMEDX is always computed from the working variable
XTWL	the normalized axial coordinate along which the wall temperature ratio distribution is prescribed
TWTTEN TWTTE	the input wall temperature ratio, its working value and the derivative of the working value w.r.t. normalized axial distance, respectively. again, TWTTEN and TWTTE are identical for the case of no smoothing with the derivative always based upon the working value

The results of the integration of the governing equations are stored in an array the length of which (i.e. the number of rows) is specified by the user (c.f. columns 10-12 on the control card by the parameter KTEST). The output of this information is separated into four categories, each of which is printed every time the output array is printed. This printing normally takes place when the output array is filled to the user specified length.

The exception to this occurs when the program is prematurely terminated at which time the contents of the output array are printed regardless of its present length.

The four blocks of information printed in the order in which they appear

(A) For PILOT1

(1) Dependent Variables And Their Derivatives - The independent variable, CHIBAR is printed followed by the 3 dependent variables, PHIBAR, the skin friction parameter, RBAR, the transformed Reynolds number based upon boundary layer height and PI, Coles wake parameter, followed by their respective derivatives. The last item printed in this group is TAULAW, the residual value of Coles skin friction law, (ideally, this parameter should be identially zero).

(2) Properties in the Physical Plane - The independent variable, CHIBAR, is printed, followed by CF, the skin friction coefficient, RTHETA, the Reynolds number based upon momentum thickness, RDLTSTR, the Reynolds number based upon boundary layer displacement thickness, RDELTA, the Reynolds number based upon boundary layer height. The remaining four columns for this output block are respectively the three integral thicknesses (measured in feet) THETA, DELSTR, DELTA and finally, DELTAX.

(3) The third block, entitled External and Wall Properties again starts with a CHIBAR column. The next three columns are related to the external velocity and wall blowing values. Specifically, column 2 contains UEBAR, the non-dimensional

local external velocity, with columns 3 and 4 containing VBARW, the wall blowing value non-dimensionalized with respect to u_{e_o} and VTLDAW which is the same wall blowing value but now non-dimensionalized with respect to the local external velocity UEI. The next two columns, entitled UEBARP and VBARWP are the local derivatives of those quantities appearing in columns 2 and 3 respectively. Columns 7 and 8 contain two special blowing parameter functions designated as ZET1 and ZETA2; the final column is a repeat of column 9 of the previous block, i.e., DELTAX.

(4) The fourth and final block contains Additional Properties. As before, columns 1 and 9 contain similar output as the previous two output blocks. Columns 2 and 3 contain special skin friction parameters respectively defined as PHI1 and PHI2. Two Clauser pressure gradient parameters, listed as BETAT1 and BETAT2 form the next two columns. Column 6 simply lists the form factor H while column 7 contains the calculated values of shear at ETASTR, i.e., TAUSTR. A Reynolds number based upon the shear velocity and the laminar sublayer, (i.e. YSPLUS) makes up column 8.

(B) For PILOT2

Again, four blocks of information are printed in the following order:

(1) Dependent Variables -

The independent variable, CHIBAR, is printed followed by the eight dependent variables, namely RBAR, PHIBAR, PI, UEBAR, VBAR, SGMATLDA, ETATILDA and CHI, in that order. The last three were not previously encountered in PILOT1 and are two of Coles scaling parameters and the streamwise Reynolds number, respectively.

(2) Derivatives of the Dependent Variables -

This second block is composed of the independent variable, CHIBAR, followed by the derivatives of the dependent variables mentioned above.

(3) Additional Properties - Group (1) -

The third block begins with the printing of the independent variable, CHIBAR, followed by the normalized axial distance, X/LREF, the normalized axial displacement, DELTAX, the Reynolds number based on axial distance, REY NO.(X), the momentum and displacement thickness, THETA and DLTASTR, respectively, followed by the Reynolds numbers based on the above, i.e., RTHETA and RDLTSTR

(4) Additional Properties - Group (2) -

The quantities CHIBAR, CHI and RTHETA are repeated for convenience and are followed by the compressible form factor, H, the skin friction coefficient, CF, and the relative errors DELTRBAR, DELSTLDA and DELZBARS.

If profiles are obtained, their output is presented in a single print block. The block is headed by a statement indicating at which station the profiles were generated and what the independent profile variable was (i.e., x, (or x/L), Re_θ, Re_x). The remaining two parameters are printed directly below.

Preceding this profile block are two smaller blocks of information representing the interpolated values of the dependent variables, their derivatives, the boundary layer properties and the external quantities corresponding to the x, or x/L, Re_θ or Re_x value which has been selected by the user. This information is immediately followed by the profiles.

For PILOT1, profile information is output with ETA, the normalized local value of the normal coordinate; followed by YLOC, the local value of the physical normal coordinate, YPLUS, the transformed Reynolds number based upon sublayer height and shear velocity, RYLOC, the Reynolds number based on local edge conditions; UPLUS, the local value of $\bar{u}/u_\tau$, UTLDA, the non-dimensional velocity as a function of ETA, UGEN, local values of Stevenson's generalized velocity and UDIF, which defines the difference in edge and local values of Stevenson's velocity.

For PILOT2, output of profile information follows a similar format. ETALOC is the normalized local value of the normal coordinate and is followed by YLOC and RYLOC which are similar to the quantities printed in the profiles for PILOT1. These are then followed by the quotient $R_{\tilde{Y}}/\tilde{\sigma}$ denoted by RYBOST, the velocity profile, UTLDA, as above, the density, temperature and viscosity profiles denoted as RHTLDA, TTILDA and VISKTI, respectively, and finally, the stagnation temperature ratio, TTRATO.

```
COMPRESSIBLE TURBULENT BOUNDARY LAYER WITH PRESSURE GRADIENT AND HEAT TRANSFER

    COMPRESSIBILITY TRANSFORMATION WITH SECOND ORDER CLOSURE IS UTILIZED

                         DIMENSIONAL  UNITS
                         -----------  -----

                       DISTANCE            FEET
                       TEMPERATURE         DEGREES-RANKINE


           PROGRAM MODES AND OPTIONS SELECTED

                 EXTERNAL MACH NUMBER DISTRIBUTION-ME(X)-INPUT

                 PERFECT GAS PROPERTIES BEING USED

                            GAMA = 1.400

                 VISCOSITY MODEL USED IS SUTHERLANDS LAW

                 WALL CONDITION----NON-ADIABATIC, TWALL(INITIAL)=   293.000

                 13  MACH NUMBER POINTS AND 13  TEMPERATURE POINTS HAVE BEEN INPUT

                 OUTPUT WILL BE IN BLOCKS OF  3

                 NO SMOOTHING HAS BEEN USED ON ANY INPUT DATA


 KEPLER + OBRIEN M=6,MAX COOL
RUN K62-10
CHECK INIT THETA
```

FREE STREAM OR REFERENCE CONDITIONS

MACH NUMBER = 5.62 TOTAL TEMPERATURE = 860.70

REYNOLDS NO./UNIT LENGTH = 7.307600E+06 REF.LENGTH = 1.00 NORMALIZED INITIAL LENGTH = 0.00

PROFILES WILL BE PRINTED AT X/L = .091000

INDICATORS

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
-0	1	3	-0	-0	1	-0	-0	1	-0	-0	3	-0	-0	-0	0	-0	1	3	-0	-0	-0	1	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0

37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72
-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0

```
$OVRIDE
REQLO   = 0.73076E+07,
LREF    = 0.1E+01,
TTF     = 0.8607E+03,
EMEO    = 0.562E+01,
TWALLO  = 0.293E+03,
XOL     = 0.0,
GAMA    = 0.14E+01,
CHIO    = 0.664E+06,
PIO     = 0.7369047E+00,
PHIO    = 0.28785E+02,
CAY1    = 0.4115E+00,
CAY2    = 0.49E+01,
CAY3    = 0.1986E+03,
CAY4    = 0.331E+03,
CAY5    = 0.3972E+03,
BETA    = 0.18E-01,
CHIBARO = 0.0,
ETASTR  = 0.5E+00,
UEBARO  = 0.1E+01,
PHIMAX  = 0.1E+04,
DCHIBRO = 0.5E+03,
DCIMAX  = 0.1E+08,
CHIMAX  = 0.53E+07,
FLT     = 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
FLE1    = 0.1E-03, 0.1E-03, 0.1E-03, 0.1E-03, 0.1E-03, 0.1E-03, 0.1E-03,
          0.1E-03,
FLE2    = 0.1E-08, 0.1E-08, 0.1E-08, 0.1E-08, 0.1E-08, 0.1E-08, 0.1E-08,
          0.1E-08,
XPROFL  = 0.91E-01, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
          0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
OPDRAY  = 1, 1, 2, 2, 1, 2, 1, 2, 1, 1, 1, 1, 1, 1, 1, 1,
VBARO   = 0.921287E-05,
ETLDAO  = 0.1E+01,
VPMIN   = 0.1E-03,
$END
```

```
$TESTER

XEL      =  0.0, 0.907E-01, 0.386E+00, 0.593E+00, 0.679E+00, 0.726E+00,
            0.8E+00, 0.9E+00, 0.1E+01, 0.2E+01, 0.3E+01, 0.4E+01, 0.5E+01,
            0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
            0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
            0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
            0.0, 0.0, 0.0, 0.0,

EMEIN    =  0.562E+01, 0.562E+01, 0.539E+01, 0.449E+01, 0.389E+01,
            0.351E+01, 0.2815E+01, 0.27E+01, 0.26E+01, 0.25E+01, 0.25E+01,
            0.25E+01, 0.25E+01, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
            0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
            0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
            0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,

EME      =  0.562E+01, 0.562E+01, 0.539E+01, 0.449E+01, 0.389E+01,
            0.351E+01, 0.2815E+01, 0.27E+01, 0.26E+01, 0.25E+01, 0.25E+01,
            0.25E+01, 0.25E+01, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
            0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
            0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
            0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,

DMEDX    =  0.22737367544323E-12, -0.77886894683365E+00, -0.43478260869563E+01,
           -0.69767441860467E+01, -0.80851063829782E+01, -0.93918918918919E+01,
           -0.11499999999999E+01, -0.11500000000001E+01, -0.10000000000001E+01,
           -0.99999999999994E-01, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
            0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
            0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
            0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,

XTWL     =  0.0, 0.907E-01, 0.386E+00, 0.593E+00, 0.679E+00, 0.726E+00,
            0.8E+00, 0.9E+00, 0.1E+01, 0.2E+01, 0.3E+01, 0.4E+01, 0.5E+01,
            0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
            0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
            0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
            0.0, 0.0, 0.0, 0.0,

TWTTEN   =  0.34E+00, 0.34E+00, 0.39E+00, 0.425E+00, 0.43E+00, 0.45E+00,
            0.45E+00, 0.45E+00, 0.45E+00, 0.45E+00, 0.45E+00, 0.45E+00,
            0.45E+00, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
            0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
            0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
            0.0, 0.0, 0.0, 0.0, 0.0, 0.0,

TWTTE    =  0.34E+00, 0.34E+00, 0.39E+00, 0.425E+00, 0.43E+00, 0.45E+00,
            0.45E+00, 0.45E+00, 0.45E+00, 0.45E+00, 0.45E+00, 0.45E+00,
            0.45E+00, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
            0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
            0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
            0.0, 0.0, 0.0, 0.0, 0.0, 0.0,

DTWDX    =  0.14210854715202E-13, 0.16931933626821E+00, 0.16908212560386E+00,
            0.58139534883708E-01, 0.42553191489361E+00, 0.0,
            0.28421709430404E-13, -0.28421709430404E-13, 0.0, 0.0, 0.0, 0.0,
            0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
            0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
            0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
            0.0, 0.0, 0.0, 0.0, 0.0,

$END
```

DEPENDENT VARIABLES

CHIBAR	RBAR	PHIBAR	PI	UEBAR	VBAR	SGMATLDA	ETATILDA	CHI
0.	1.196353E+05	2.878500E+01	7.369047E-01	1.000000E+00	9.212870E-06	2.731701E-01	1.000000E+00	6.640000E 05
5.000000E+02	1.196694E+05	2.878974E+01	7.380822E-01	9.998265E-01	9.063328E-06	2.733098E-01	1.001664E+00	6.865066E 05
1.000000E+03	1.197139E+05	2.879459E+01	7.392677E-01	9.996508E-01	8.924809E-06	2.734526E-01	1.003343E+00	7.079854E 05

DERIVATIVES OF THE DEPENDENT VARIABLES

CHIBAR	RBARP	PHIBARP	PIP	UEBARP	VBARP	SGMATLDP	ETATLDAP	CHIP
0.	6.780238E-02	9.390632E-06	2.346094E-06	-3.448676E-07	-3.092423E-10	2.760885E-07	3.313823E-06	4.613788E 01
5.000000E+02	6.859083E-02	9.587966E-06	2.362970E-06	-3.492483E-07	-2.875881E-10	2.826066E-07	3.343177E-06	4.393199E 01
1.000000E+03	6.934098E-02	9.775779E-06	2.378982E-06	-3.533883E-07	-2.669620E-10	2.885037E-07	3.371410E-06	4.203044E 01

ADDITIONAL PROPERTIES-GROUP(1)

CHIRAP	X/LREF	DELTAX	REY NO.(X)	THETA	DLTASTR	RTHETA	RDLTSTR
0.	9.086431E-02	9.086431E-02	6.640338E+05	6.608370E-03	6.365864E-02	4.829378E+04	4.652156E+05
5.000000E+02	9.394419E-02	9.394419E-02	6.871961E+05	6.601568E-03	6.357742E-02	4.829007E+04	4.650650E+05
1.000000E+03	9.688344E-02	9.688344E-02	7.093416E+05	6.594741E-03	6.349683E-02	4.828405E+04	4.648983E+05

ADDITIONAL PROPERTIES-GROUP (2)

CHIBAR	CHI	RTHETA	H	CF	DELTRBAR	DELSTLDA	DELZBARS
0.	6.640000E+05	4.829378E+04	9.633033E+00	6.694862E-04	0.	7.527278E-05	-2.961034E-03
5.000000E+02	6.865066E+05	4.829007E+04	9.630655E+00	6.694463E-04	-1.452028E-07	7.172572E-05	4.070009E-03
1.000000E+03	7.079854E+05	4.828405E+04	9.628404E+00	6.694165E-04	-2.914566E-07	1.770783E-05	4.388428E-03

PROFILES AT STATION X/L = .091000

RTHETA = 4.829362E+04 REX = 6.650542E+05

DEPENDENT VARIABLES.THEIR DERIVATIVES.AND ADDITIONAL PROPERTIES

CHIBAR= 2.20291E+01 RBAR= 1.19637E+05 PHI= 2.87852E+01 PI= 7.36957E-01 UEBAR= 9.99992E-01 VBAR= 9.20628E-06
STILDA= 2.73176E-01 ETILDA= 1.00007E+00 CHI= 6.64992E+05 RBARP= 6.78371E-02 PHIP= 9.39933E-06 PIP= 2.34684E-06
UEBARP=-3.45061E-07 VBARP=-3.08288E-10 STLDAP= 2.76376E-07 ETLDAP= 3.31512E-06 CHIP= 4.60407E+01
DELTAX= 9.10000E-02 THETA= 6.60807E-03 DELSTR= 6.36551E-02 RDLSTR= 4.65209E+05 H= 9.63293E+00 CF= 6.69484E-04

EXTERNAL AND WALL PROPERTIES

EMEI= 5.61977E+00 DMEDXI=-7.82495E-01 WBARI= 3.40051E-01 DTWDXI= 1.69319E-01 EME= 6.31635E+00 EMTLDA=-8.63320E-01
DLUDXI=-1.90313E-02 DLRDXI= 6.01042E-01 DLVDXI= 2.71191E-01 DEMTDXI= 3.28602E-02 DTETDXI= 3.28602E-02
TWTE= 2.48793E+00 RHWRHE= 4.01940E-01 MUWMUE= 2.52607E+00 EWI= 1.85828E-01

ETA	Y/LREF	RYLOC	RYBOST	UTILDA	RHTLDA	TTILDA	MUTLDA	TT/TTE
0.	0.	0.	0.	0.	4.019402E-01	2.487932E+00	2.526066E+00	3.400508E-01
4.262164E-03	3.715832E-03	2.715637E+04	8.758879E+03	5.441141E-01	3.081546E-01	3.245124E+00	3.185433E+00	6.991384E-01
8.629030E-03	7.522945E-03	5.497985E+04	1.751776E+04	6.031945E-01	3.223472E-01	3.102245E+00	3.066192E+00	7.381285E-01
1.282270E-02	1.117904E-02	8.169980E+04	2.627664E+04	6.382164E-01	3.336969E-01	2.996732E+00	2.976663E+00	7.612412E-01
1.688413E-02	1.471989E-02	1.075772E+05	3.503552E+04	6.635376E-01	3.435489E-01	2.910794E+00	2.902789E+00	7.779519E-01
2.083534E-02	1.816463E-02	1.327524E+05	4.379440E+04	6.836500E-01	3.525145E-01	2.836762E+00	2.838446E+00	7.912250E-01
2.469007E-02	2.152525E-02	1.573128E+05	5.255328E+04	7.005479E-01	3.609310E-01	2.770613E+00	2.780390E+00	8.023768E-01
2.845756E-02	2.480982E-02	1.813173E+05	6.131216E+04	7.152897E-01	3.690095E-01	2.709958E+00	2.726680E+00	8.121056E-01
3.214434E-02	2.802402E-02	2.048076E+05	7.007104E+04	7.285023E-01	3.768947E-01	2.653261E+00	2.676056E+00	8.208253E-01
3.575514E-02	3.117198E-02	2.278138E+05	7.882992E+04	7.405860E-01	3.846926E-01	2.599478E+00	2.627654E+00	8.288000E-01
3.929348E-02	3.425677E-02	2.503584E+05	8.758879E+04	7.518102E-01	3.924849E-01	2.547868E+00	2.580856E+00	8.362073E-01
4.276197E-02	3.728067E-02	2.724579E+05	9.634767E+04	7.623636E-01	4.003377E-01	2.497891E+00	2.535203E+00	8.431721E-01
4.616259E-02	4.024539E-02	2.941249E+05	1.051066E+05	7.723825E-01	4.083060E-01	2.449144E+00	2.490353E+00	8.497840E-01
4.949682E-02	4.315223E-02	3.153689E+05	1.138654E+05	7.819675E-01	4.164376E-01	2.401320E+00	2.446043E+00	8.561096E-01
5.276577E-02	4.600216E-02	3.361971E+05	1.226243E+05	7.911940E-01	4.247747E-01	2.354189E+00	2.402067E+00	8.621987E-01
5.597028E-02	4.879591E-02	3.566146E+05	1.313832E+05	8.001195E-01	4.333559E-01	2.307572E+00	2.358270E+00	8.680890E-01
5.911095E-02	5.153400E-02	3.766254E+05	1.401421E+05	8.087880E-01	4.422167E-01	2.261335E+00	2.314529E+00	8.738098E-01
6.218825E-02	5.421684E-02	3.962323E+05	1.489010E+05	8.172331E-01	4.513907E-01	2.215376E+00	2.270752E+00	8.793831E-01
6.520249E-02	5.684472E-02	4.154376E+05	1.576598E+05	8.254808E-01	4.609100E-01	2.169621E+00	2.226871E+00	8.848262E-01
6.815394E-02	5.941785E-02	4.342428E+05	1.664187E+05	8.335508E-01	4.708053E-01	2.124020E+00	2.182837E+00	8.901520E-01
7.104278E-02	6.193639E-02	4.526490E+05	1.751776E+05	8.414581E-01	4.811066E-01	2.078542E+00	2.138619E+00	8.953704E-01
7.386917E-02	6.440049E-02	4.706573E+05	1.839365E+05	8.492135E-01	4.918431E-01	2.033169E+00	2.094203E+00	9.004886E-01
7.663325E-02	6.681026E-02	4.882687E+05	1.926953E+05	8.568248E-01	5.030433E-01	1.987900E+00	2.049585E+00	9.055117E-01
7.933517E-02	6.916585E-02	5.054839E+05	2.014542E+05	8.642971E-01	5.147351E-01	1.942747E+00	2.004775E+00	9.104430E-01
8.197511E-02	7.146739E-02	5.223043E+05	2.102131E+05	8.716333E-01	5.269455E-01	1.897729E+00	1.959797E+00	9.152845E-01
8.455327E-02	7.371508E-02	5.387311E+05	2.189720E+05	8.788345E-01	5.397006E-01	1.852879E+00	1.914681E+00	9.200369E-01
8.706992E-02	7.590914E-02	5.547659E+05	2.277309E+05	8.859003E-01	5.530252E-01	1.808236E+00	1.869469E+00	9.247000E-01
8.952536E-02	7.804984E-02	5.704107E+05	2.364897E+05	8.928289E-01	5.669426E-01	1.763847E+00	1.824215E+00	9.292725E-01
9.191999E-02	8.013752E-02	5.856681E+05	2.452486E+05	8.996173E-01	5.814741E-01	1.719767E+00	1.778977E+00	9.337526E-01
9.425427E-02	8.217259E-02	6.005410E+05	2.540075E+05	9.062619E-01	5.966380E-01	1.676058E+00	1.733827E+00	9.381376E-01
9.652876E-02	8.415553E-02	6.150329E+05	2.627664E+05	9.127579E-01	6.124497E-01	1.632787E+00	1.688840E+00	9.424247E-01
9.874412E-02	8.608692E-02	6.291480E+05	2.715253E+05	9.191000E-01	6.289199E-01	1.590028E+00	1.644104E+00	9.466101E-01
1.009011E-01	8.796740E-02	6.428912E+05	2.802841E+05	9.252821E-01	6.460543E-01	1.547858E+00	1.599711E+00	9.506900E-01
1.030005E-01	8.979775E-02	6.562679E+05	2.890430E+05	9.312976E-01	6.638519E-01	1.506360E+00	1.555763E+00	9.546599E-01
1.050435E-01	9.157881E-02	6.692844E+05	2.978019E+05	9.371395E-01	6.823038E-01	1.465623E+00	1.512368E+00	9.585153E-01
1.070310E-01	9.331156E-02	6.819478E+05	3.065608E+05	9.428003E-01	7.013917E-01	1.425737E+00	1.469639E+00	9.622511E-01
1.089643E-01	9.499706E-02	6.942659E+05	3.153197E+05	9.482722E-01	7.210858E-01	1.386798E+00	1.427698E+00	9.658623E-01
1.108448E-01	9.663652E-02	7.062476E+05	3.240785E+05	9.535469E-01	7.413430E-01	1.348903E+00	1.386670E+00	9.693433E-01
1.126740E-01	9.823125E-02	7.179023E+05	3.328374E+05	9.586159E-01	7.621048E-01	1.312156E+00	1.346687E+00	9.726886E-01
1.144535E-01	9.978266E-02	7.292406E+05	3.415963E+05	9.634705E-01	7.832950E-01	1.276658E+00	1.307885E+00	9.758924E-01
1.161852E-01	1.012924E-01	7.402739E+05	3.503552E+05	9.681016E-01	8.048175E-01	1.242518E+00	1.270403E+00	9.789486E-01
1.178709E-01	1.027620E-01	7.510145E+05	3.591141E+05	9.724999E-01	8.265542E-01	1.209842E+00	1.234383E+00	9.818513E-01
1.195128E-01	1.041935E-01	7.614758E+05	3.678729E+05	9.766560E-01	8.483627E-01	1.178741E+00	1.199970E+00	9.845942E-01
1.211131E-01	1.055846E-01	7.716721E+05	3.766318E+05	9.805603E-01	8.700754E-01	1.149326E+00	1.167311E+00	9.871708E-01
1.226742E-01	1.069496E-01	7.816185E+05	3.853907E+05	9.842031E-01	8.914978E-01	1.121708E+00	1.136551E+00	9.895748E-01
1.241986E-01	1.082766E-01	7.913314E+05	3.941496E+05	9.875742E-01	9.124095E-01	1.095999E+00	1.107839E+00	9.917996E-01
1.256891E-01	1.0957[illegible]E-01	8.008280E+05	4.029085E+05	9.906638E-01	9.325642E-01	1.072312E+00	1.081319E+00	9.938386E-01
1.271485E-01	1.108504E-01	8.101264E+05	4.116673E+05	9.934615E-01	9.516934E-01	1.050759E+00	1.057135E+00	9.956849E-01
1.285798E-01	1.120942E-01	8.192548E+05	4.204262E+05	9.959570E-01	9.695097E-01	1.031449E+00	1.035429E+00	9.973318E-01
1.299861E-01	1.133243E-01	8.282064E+05	4.291851E+05	9.981401E-01	9.857133E-01	1.014494E+00	1.016339E+00	9.987725E-01
1.313691E-01	1.145300E-01	8.370181E+05	4.379440E+05	1.000000E+00	1.000000E+00	1.000000E+00	1.000000E+00	1.000000E+00

CASE TERMINATED AFTER PRINTING ONE SMALL BLOCK OF 3 INTEGRATION STEPS AS PER USER REQUEST

VIII. DESCRIPTION OF PROGRAM SUBROUTINES

Deck Name	
BLOCK DATA	All pre-set data and program constants are stored and initialized in this routine. The pre-set data include default initial values of some of the dependent variables, program test parameters, and integration tolerances. In addition, the results of the quadrature integration done by subroutine "INTGRL" using Coles wake parameter in the form $w(\eta) = 6\eta^2 - 4\eta^3$ are included. A form of this routine is contained in both PILOT1 and PILOT2 and much of the data contained in it are common to both programs.
BLPROP	A form of this routine is contained in both PILOT1 and PILOT2 and calculates the required boundary layer properties, the profile point test quantities (i.e., axial location, local Reynolds number and local Reynolds number based on momentum thickness) and the solution control relative errors on RBAR, STILDA and ZBAR where appropriate.
BOUNDE	This routine, a form of which appears in both PILOT1 and PILOT2, determines the local axial coordinate and then finds, by LaGrangian interpolation of existing tables of edge and wall conditions and their derivatives, the local values of these quantities. In addition, this routine calculates

certain quantities which depend only on these external and wall conditions and certain logarithmic derivatives which are needed elsewhere in the program.

CHSUB — This routine is called by the integration package once after every integration step has been completed. It may be used to perform certain tests on the results of the integration. At present, it is a dummy routine in both PILOT1 and PILOT2.

COEFFS — In PILOT1, this routine calculates the 12 coefficients required to find the solution of a system of 3 ordinary differential equations in the dependent variables PHI, RBAR and PI. In PILOT2 it evaluates the 72 coefficients required to solve the system of 8 ordinary differential equations in RBAR, PHI, PI, UEBAR, UBAR, STILDA, ETILDA, and CHI.

DATPRP — This routine is used in PILOT1 only to compute the remaining reference conditions from those which are input, to evaluate the remaining external conditions from those which are input, to set up the smoothing operation on the input external velocity and to generate the derivatives of the external quantities.

DERSUB This routine is called by the integration package to evaluate the derivatives of the dependent variables. It, in turn, contains the logic which calls routines which determine the local edge conditions, calculate the sublayer properties, determine the quantities needed to evaluate the coefficients required in order to solve the matrix of ordinary differential equations, and invert that matrix. A form of this routine appears in both PILOT1 and PILOT2.

ERROR This routine prints all error messages and sets up the standard error termination made used by both PILOT1 and PILOT2. When termination is complete, this routine calls the main program "MAIN" for processing of the next case or run termination. The PILOT2 version of this routine contains all the error messages of PILOT1 plus 4 additional ones specific to its computational procedure.

FPRIM This function sub-program is contained in PILOT2 only and is used by the service routine "NERIT" to evaluate the derivative of the function required to find the value of USTLDAO($\tilde{u}_{s_o}$) associated with a particular value of PHI (φ). The information is required in the calculation of an initial value of VBAR($\bar{V}$) for a leading edge problem.

FUNCT

This function sub-program in PILOT1 is called by the quadrature integration routine "TRAPIN" which, in turn, is called by "INTGRL" to evaluate the integrand required to find the integral $\int_0^{\eta}[w(\eta)]^P [\ell n\eta]^Q\, d\eta$. In PILOT2, in addition to the above, this routine is called by the "NERIT" to evaluate the function required to find the value of USTLDAO ($\tilde{u}_{s_o}$) associated with a particular value of PHI(φ) required in the calculation of an initial value of VBAR($\bar{V}$) for a leading edge problem.

GETFS

This routine is common to both PILOT1 and PILOT2 in nearly the same form. Given certain dependent variables it calculates the function F(ETA) [$F(\eta)$] for ETA equal to ETASTR and 1 ($\eta=\eta^*$ and $\eta=1$). These functions are required, in turn, to evaluate certain of the coefficients of the differential equations.

GETQS — This routine, except for common blocks, is identical in both PILOT1 and PILOT2 and evaluates the functions Q(ETA)[$Q(\eta)$] and their derivatives; for ETA equal to ETASTR and 1, (i.e., $\eta=\eta^*$ and $\eta=1$) using the results of the quadrature integration and the dependent variable, PI.

GETYSP — This routine, except for common blocks, is also identical in PILOT1 and PILOT2 and obtains YSPLUS, the laminar sublayer height, by solving an equation which contains YSPLUS, implicitly, given a value of the velocity VWPLUS (V_w^+).

INIT2 — In PILOT1, this routine calculates the various functional forms of Coles wake parameter and its derivative as a function of the normalized vertical coordinate, ETA(η) and computes the initial value of the dependent variable RBAR($\bar{R}$) from certain of the other initial values of the dependent variables. In PILOT2, the role of this routine is expanded to include in addition to the above, the calculation of other initial dependent quantities.

INPUT — This routine is responsible for all program input in both programs. In PILOT1, only external velocity input may be smoothed. The remainder of any smoothing operations on input data and the calculation of the derivatives of the external and wall quantities is left to subroutine "DATPRP". In PILOT2 subroutine "INPUT" handles all of the above operations.

INTGRL — This routine, except for common blocks, is the same in both programs. It obtains, by quadrature, the values of the integral $\int_0^{\eta} [w(\eta)]^P [\ell n\eta]^Q d\eta$ for $0 \le \eta \le \eta^*$ and for $0 \le \eta \le 1$. The results of the integration are stored as a three-dimensional array whose indices are P, Q, and η; η taking on only the value of the upper limits of the integration.

INT1A — This closed routine is the bulk of the integration package used in these programs. It is basically a fifth-order integration routine which uses a classical fourth-order Runge-Kutta formula in conjunction with Richardson's Extrapolation for variable step size with the computing interval varied to meet local relative truncation error tolerances, independently, on each dependent variable. The routine uses the single precision mode exclusively and is identical in both PILOT1 and PILOT2.

LAGDER

This service routine, identical in both programs, numerically calculates the derivative of a function using the LaGrangian method.

LAGR

This service routine, when given tables of an independent variable, X, and a function of that variable, Y = F(X), will find, by LaGrangian interpolation, up to tenth order, the value of Y_n associated with a particular argument, X_n. PILOT1 and PILOT2 contain identical versions of this routine.

LGRANG

This is another service routine; again, identical in PILOT1 and PILOT2 which interpolates to any desired order from tabulated values of one or more functions of a single independent variable. It is similar to LAGR above, but more general.

LMDA

This routine, identical, except for common blocks, between PILOT1 and PILOT2, calculates the definite integrals LAMDA(ETASTR) $\lambda(\eta^*)$ and LAMDA(1) [$\lambda(1)$] and the related quantities, SIGMA (Σ) and OMEGA (Ω).

MAIN	This subroutine is, in both programs, the true "MAIN" program. It initially sets all internal program switches, initializes the dependent variables for the calculation of the initial derivatives and sets and increments all program counters. Program termination in a non-error mode is also handled by this routine. It is the only routine which may be assumed to contain all common blocks. The different versions of this routine in PILOT1 and PILOT2 are primarily due to the different number of dependent variables handled by each program.
NERIT	This service routine when given a function F(x), finds the zeros of F(x) within some prescribed interval (a,b). This routine is required in PILOT2 only.
OUTPUT	This routine, once integration has begun, processes all output in both programs. A separate entry point is provided for processing the output of profile information. The forms of this routine are very similar in the two programs, the differences being due primarily to the different quantities which are output in each.

PARDRV — This routine is used <u>only in PILOT2</u> and calculates the values of certain partial derivatives needed in evaluating the coefficients for the matrix of ordinary differential equations.

PILOT1/2 — The dummy main program in both PILOT1 and PILOT2. Its only function is to call the true main program, subroutine "MAIN" and provide for access to "MAIN" from other subprograms.

PRFILE — This routine, contained in both PILOT1 and PILOT2, sets up the necessary interpolations of computed properties which are required in order to compute profiles at the user-specified points. Its form is very much the same in both programs, the differences being associated with the information contained in the output array being interpolated, and the subroutine sequence called in generating the profile information.

PRINT — This routine, a form of which appears in both programs, prints the program title, all unit designations, option selections, case identifying information, free stream or reference conditions and profile point selections.

PROFIL — Both PILOT1 and PILOT2 contain very similar versions of this routine which calculates all profile properties at user-specified profile points. The differences in the two versions have to do with parameters at the beginning of the routine in the PILOT2 version. It should be noted that this routine, unlike its predecessor of Reference 1, is <u>not</u> required in the normal course of the program computation but only if and when profile information is requested.

SIMQ — The service routine, identical in both programs, except for a single common block in the PILOT2 version, solves the system of linear ordinary differential equations AY = B by matrix inversion.

SMOOTH — This service routine, with identical versions in both PILOT1 and PILOT2 except for a single common block, performs local smoothing of a tabulated function by the method of least squares. This smoothing operation is an option in both programs.

SUBLYR — This routine is used <u>only by PILOT2</u> and generates all sublayer properties required in the solution of the system of differential equations.

TRAPIN — This is a service routine which performs numerical integration by quadratures using a trapezoidal rule. The versions in PILOT1 and PILOT2 are identical except for one common block.

UNITS This service routine is contained only in PILOT2 and makes all the necessary unit conversions between English system engineering units and S.I. (International) units for all input and output information. The routine has 2 separate entry points to facilitate the conversions. As implied above, the PILOT1 program is written for use with English system engineering units only.

VSTART This routine is used only in PILOT2 and is used only for a leading edge problem (i.e. for generating an initial value of VBAR when profile information is not available). It accomplishes this by finding for an initial specified value of the dependent variable, PHI, (i.e., $\varphi = \varphi_o$) a value of USTLDA (i.e., $\tilde{u}_s = \tilde{u}_{so}$) which satisfies the transcendental equation $G(\tilde{u}_s, \varphi) - F(\tilde{u}_s) = 0$ using a Newton-Raphson iteration technique.

IX. PROGRAM USE, OPERATION. AND LIMITATIONS

Programs PILOT1 and PILOT2 have been designed primarily for use on the CDC 6600 series computer. All coding has been done in CDC 6600 FORTRAN which is compatible with standard FORTRAN II and FORTRAN IV languages. The source programs for PILOT1 and PILOT2 are approximately 2500 and 3000 cards, respectively, and have been compiled and executed on both the standard run FORTRAN and extended FORTRAN CDC Systems. FORTRAN logical 5 (Tape 5) and logical 6 (Tape 6) units are used for input and output, respectively, for both programs. No other intermediate utility tapes are required.

An effort was made in the development of these programs to write them in a way which would avoid the necessity to overlay any portion of either of them. This has been accomplished in that the core requirements for loading and execution of each are modest. The program logic for PILOT1 (including all common blocks) requires less than $60{,}000_8$ core for loading and approximately $37{,}000_8$ core for execution on the CDC 6600. For PILOT2, $65{,}000_8$ core is required for loading while 43,000 is necessary for execution. Both programs may be batch-processed and any number of cases may be input at one time. Program execution time depends to some extent on the type of input data being processed but, in general, will be 1/2 second or less per integration step for both PILOT1 and PILOT2.

Most of the program limitations have been mentioned elsewhere in this text but are summarized, for convenience, below:

(1) At present, PILOT2 and PILOT1 write 29 and 32 variables to the output array, respectively.

(2) Only 3 dumpswitch settings are presently available in both programs.

(3) Output print blocks are limited to a maximum of 50 lines per block in both programs.

(4) Both PILOT1 and PILOT2 have provision, at present, for processing a maximum of 20 profile points.

(5) Both programs require the external data (i.e., edge and/or wall condition variations) to be specified within 50 data points.

(6) Calculation of profiles are done at fixed increments in the vertical normalized coordinate ETA and provide for 51 profile points at any selected profile station. This applies to PILOT1 only.

SUMMARY OF PRE-SET DATA

(I) Information Common to PILOT1 and PILOT2

CAY1	= 0.4115	LREF	= 1.0
CAY2	= 4.90	NINTPT	= 1
BETA	= .018	DCIMAX	= 10^7
ETASTR	= 0.5	VPMIN	= .0001
PIE	= 3.14159	CHIMAX	= 10^8
DBDVTW	= 0.25	PHIMAX	= 1000

(II) Information Contained Only in PILOT1

ELE1	DEPENDENT VARIABLE	ELE2
1.0×10^{-4}	PHI(φ)	1.0×10^{-9}
↓	RBAR($\bar{R}$)	↓
	PI (π)	

DCHIBR = 500.
CHIBAR = 0.
XO = 0.
VBAR = 0.
DVWDX = 0.
YSPLSI = 10.6

ORDRAY ELEMENT	FORMAL PARAMETER	SUBROUTINE	VALUE
1	IORDR1	LAGDER	2
2	IORDR2	LAGDER	2
3	IORDR3	LAGDER	2
4	IORDR4	LGRANG	2
5	IORDR5	LAGR	1
6	IORDR6	LGRANG	2
7	IORDR7	LAGR	1
8	IORDR8	LGRANG	2

(III) Information Contained Only in PILOT2

CAY3	= 198.6	XOL	= 0.
CAY4	= 331.	DCHIBRO	= 500.
CAY5	= 397.2	CHIBARO	= 0.
YSPLUS	= 10.6	UEBARO, ETLDAO	= 1.0
CHIO	= 0.	PHIO	= 15.0

PIO = 0.6

ELE1	DEPENDENT VARIABLE	ELE2
1.0×10^{-4}	RBAR($\bar{R}$)	1.0×10^{-9}
↓	PHI(φ)	↓
	PI(π)	
	UEBAR($\bar{u}_e$)	
	VBAR($\bar{V}$)	
	STILDA($\tilde{\sigma}$)	
	ETILDA($\tilde{\eta}$)	
	CHI(χ)	

ORDRAY ELEMENT	FORMAL PARAMETER	SUBROUTINE	VALUE
1	IORDR1	LAGDER	2
2	IORDR2	LAGDER	2
3	IORDR3	NOT USED	2
4	IORDR4	LGRANG	2
5	IORDR5	LAGR	1
6	IORDR6	LGRANG	2
7	IORDR7	LAGR	1
8	IORDR8	LGRANG	2
9	IORDR9	LAGR	1
10	IORDR1	LAGR	1

TABLE OF SYMBOLS AND PROGRAM NOTATION

AA or A	a 1-D array of coefficients used to solve the system of ordinary differential equations
BETA (β)	mixing length constant
BLOW1	name list name used to input VBAR vs x
BETA1 (β_{T_1})	output array defining Clauser's pressure gradient parameter, $-\delta^* \dfrac{d\ln u_e}{dx} \Big/ \dfrac{c_f}{2}$
BETA2 (β_{T_2})	output array defining pressure gradient parameter with mass transfer, $-\delta \dfrac{d\ln u_e}{dx} \Big/ (\dfrac{c_f}{2} + V_w)$
C	the solution vector for the system of ordinary differential equations
CHIBAR ($\bar{\chi}$)	streamwise independent variable of the system
CHI (χ)	the physical streamwise Reynolds number, a dependent variable
CHIO (χ_o)	the initial value of the dependent variable, CHI
CHIP (χ')	the derivative of the dependent variable, CHI
CHIMAX	the maximum value of CHI - an input used for normal case termination
COLD	the solution vector, C, before being operated on by the matrix inversion routine, SIMQ
CBAR ($\bar{c}_f$)	the skin friction coefficient in the transformed constant property plane
CF (c_f)	the skin friction coefficient in the physical plane
CAY1 (k_1)	constant, 0.4115
CAY2 (k_2)	constant, 4.9
CAY3 (k_3)	constant, 198.6
CAY4 (k_4)	constant, 331.
CAY5 (k_5)	constant, 397.2
CP	table of pressure coefficients input via PCOEFF namelist

DCHIBR ($\Delta\bar{\chi}$)	the initial increment of CHIBAR	
DCIMAX	the maximum permitted increment in CHIBAR between integration steps	
DPEDX (dp_e/dx)	lbs ft^2/ft	The derivatives of the external pressure and velocity, respectively
DUEDX (dU_e/dx)	ft/sec/ft	
DELTAX (Δx)	the axial displacement along the body	
DLTASTR (δ*)	the notation used in the output format for the physical displacement thickness	
DFMTDXI $d\tilde{m}_e/d(x/L)$	non-dimensional derivative of parameter FMTLDA ($\tilde{m}_e$)	
DLRDXI $d\ ln\rho_e/d(x/L)$	non-dimensional logarithmic derivative of external density	
DLUDXI $d ln U_e/d(x/L)$	non-dimensional logarithmic derivative of external velocity	
DLVDXI $d ln\mu_e/d(x/L)$	non-dimensional logarithmic derivative of external viscosity	
DMEDX($dM_e/dx/L$)	array containing the derivatives of Mach number points in the XEL table	
DMEDXI	derivative of Mach number ar the specific point, XLI	
DRBAR	relative error on RBAR	
DTETDXI	non-dimensional derivative of (T_e/T_t)	
DTWDX ($d\bar{W}/dx$)	array containing the derivatives of wall temperature ratio at the specific point, XLI	
DTWDXI	derivative of wall temperature ratio at the specific point, XLI	
DSTLDA ($\Delta\tilde{\sigma}$)	relative error on $\tilde{\sigma}$	
DVWDX	array containing derivatives of VBAR at each input point, 1/ft.	

ELE1	a 1-D array containing the upper bound of the local relative truncation errors
ELE2	a 1-D array containing the lower bound or relative zero for each dependent variable
EMEO(M_{eo})	initial or reference value of the external Mach number
ETABAR($\bar{\eta}$)	transformed normal coordinate normalized w.r.t. boundary layer thickness
ETASTR($\bar{\eta}^*$)	specified (constant) value of ETABAR = 0.5
ETATILDA($\tilde{\eta}$)	the name used in the output for one of Coles scaling parameters
ETLDA($\tilde{\eta}_o$)	the initial value of the dependent variable, ETATILDA
ETATLDAP($\tilde{\eta}'$)	the output name of the derivative of ETATILDA
EME(M_e)	the array of smoothed values of the input Mach No. (If no smoothing is done, this array contains the same information as the EMEIN array.
EMEI	local value of the external Mach number
EMEIN	table of input values of external Mach numbers
ETARAY($\bar{\eta}$)	one-dimensional array of $\bar{\eta} = \bar{y}/\bar{\delta}$
ETALOC(η)	one-dimensional array of $\eta = y/\delta$
ETA($\bar{\eta}$)	output block in PILOT1 defining $\bar{\eta}$
FME(m_e)	local value of $(T_{te}/T_e - 1)$
FMTLDA($\tilde{m}_e$)	local value of (T_{te}/T_e)
FS(f_s)	value of $d\ln\tilde{\rho}\tilde{\mu}/\partial\tilde{u})$ at sub-layer beight
FWI(f_w)	value of $(\partial\ln\tilde{\rho}\tilde{\mu}/\partial\tilde{u})$ at wall
GAMA(γ)	the specific heat ratio of the gas
H (H)	the compressible form factor
HBAR($\bar{H}$)	the transformed form factor

IERR	an error indicator set by the integration package
IINTRL	running counter which indicates the number of integration steps completed
ITEXT	a print switch used by the integrator for printing a history of the computing interval and reasons for its change
KE	an error indicator printed by LAGR
KTEST	the input integer with which the user selects the number of lines ineach output print block
LREF(L_{ref})	reference length (ft. or meters)
LAMDA(1,1) (Λ_1^*)	integral of $\tilde{u}d\bar{\eta}$ from 0 to $\bar{\eta}^*$
LAMDA(1,2) (Δ_1^1)	integral of $\tilde{u}d\bar{\eta}$ from 0 to 1
LAMDA(2,1) (Λ_2^*)	integral of $\tilde{u}^2 d\eta$ from 0 to $\bar{\eta}^*$
LAMDA(2,2) (Λ_2^1)	integral of $\tilde{u}^2 d\eta$ from 0 to 1
MACH	the namelist name used for input of the external Mach number distribution
MUWMUE($\tilde{\mu}_w$)	wall-to-edge viscosity ratio at point, XLI
MUTLDA($\tilde{\mu}$)	ratio of viscosity at point y/L in the boundary layer to edge viscosity at point, XLI
NOXPTS	the number of axial points along which external information is supplied
NPRFPT	the number of points at which profiles are desired
NINTPT	the number of integration steps between adjacent lines of printout in an output block
OVRIDE	the namelist name used for input of all required program input information
ORDRAY	one-dimensional array of integers used to change order of Lagrangian interpolation and differentiation
OMEGA(Ω)	non-dimensional constant property momentum thickness

PI(π)	the working value of the wake parameter, a dependent variable
PIO(π_o)	the initial value of the dependent variable PI
PIP(π')	the derivative of the dependent variable PI
PHI(φ)	the working value of the incompressible skin friction parameter, a dependent variable
PHIBAR($\bar{\varphi}$)	the output name used for the dependent variable, PHI
PHIBRO($\bar{\varphi}_o$)	the initial value of PHI
PHIMAX	the maximum permitted value of the dependent variable, PHI (i.e., if PHI exceeds this value, an error message is printed and the program computation terminates
PHIBARP($\bar{\varphi}'$)	the derivative of the dependent variable PHI
PREF	reference static pressure, input in pounds per sq. inch
PTREF	reference total pressure, input in pounds per sq. inch
PRESSR	namelist name used for input of external pressure distribution
PCOEFF	namelist name used for input of external pressure coefficient distribution
PE(p_e)	table of pressures input via PRESSR namelist
PHI1	output array defining $(\bar{C}_f/2)^{\frac{1}{2}}$
PHI2	output array defining $(\bar{C}_f/2 + \tilde{V}_w)^{\frac{1}{2}}$
QREF	reference dynamic pressure, input in pounds per sq. inch
RBAR($\bar{R}$)	the transformed Reynolds number based on boundary layer height and initial unit Reynolds number - a dependent variable
RBARP($\bar{R}'$)	the derivative of the dependent variable RBAR

RDLTSTR($R_{\delta *}$) — the output name used for the local value of the physical Reynolds number based on the displacement thickness

RTHETA(R_{e_θ}) — the output name used for the local value of the physical Reynolds number based on the momentum thickness

REQLO — initial value of unit Reynolds number, 1/ft. or 1/meters

RHOEO — the initial value of the density of the external flow - slugs ft/^{3}

REX(Re_x) — value of the unit Reynolds number at XLI

RHWRHE ($\tilde{\rho}_w$) — wall-to-edge density ratio at point, XLI

RHTLDA ($\tilde{\rho}$) — ratio of the density at point (y/L) in the boundary layer to the density of the external flow at point XLI

RYLOC (R_Y) — Reynolds number based on local edge conditions and physical height in the boundary layer

RYBOST ($R\bar{y}/\tilde{\sigma}$) — output block in profile calculation

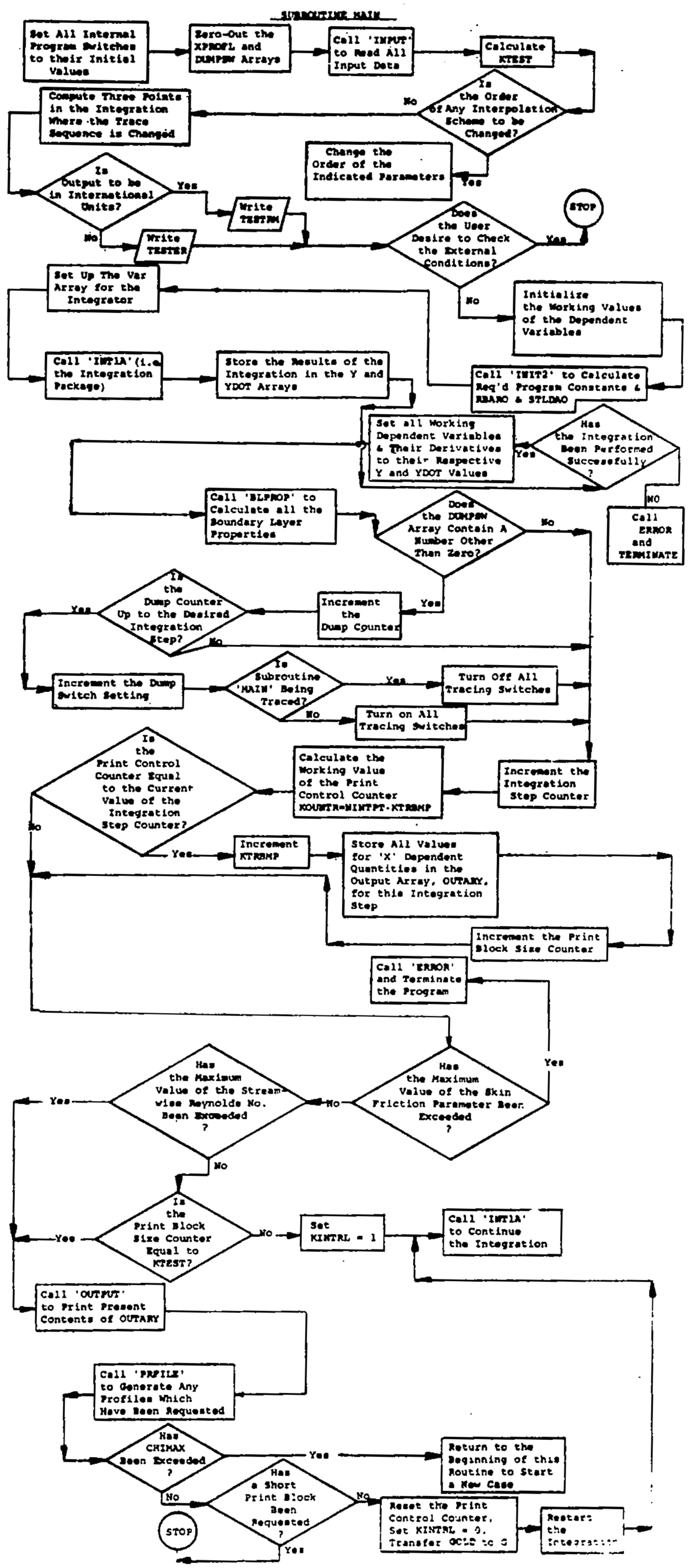
SPEED — the name list name used for input of the external velocity distribution

SGMATILDA ($\tilde{\sigma}$) — the program output name used for one of Coles' scaling parameters

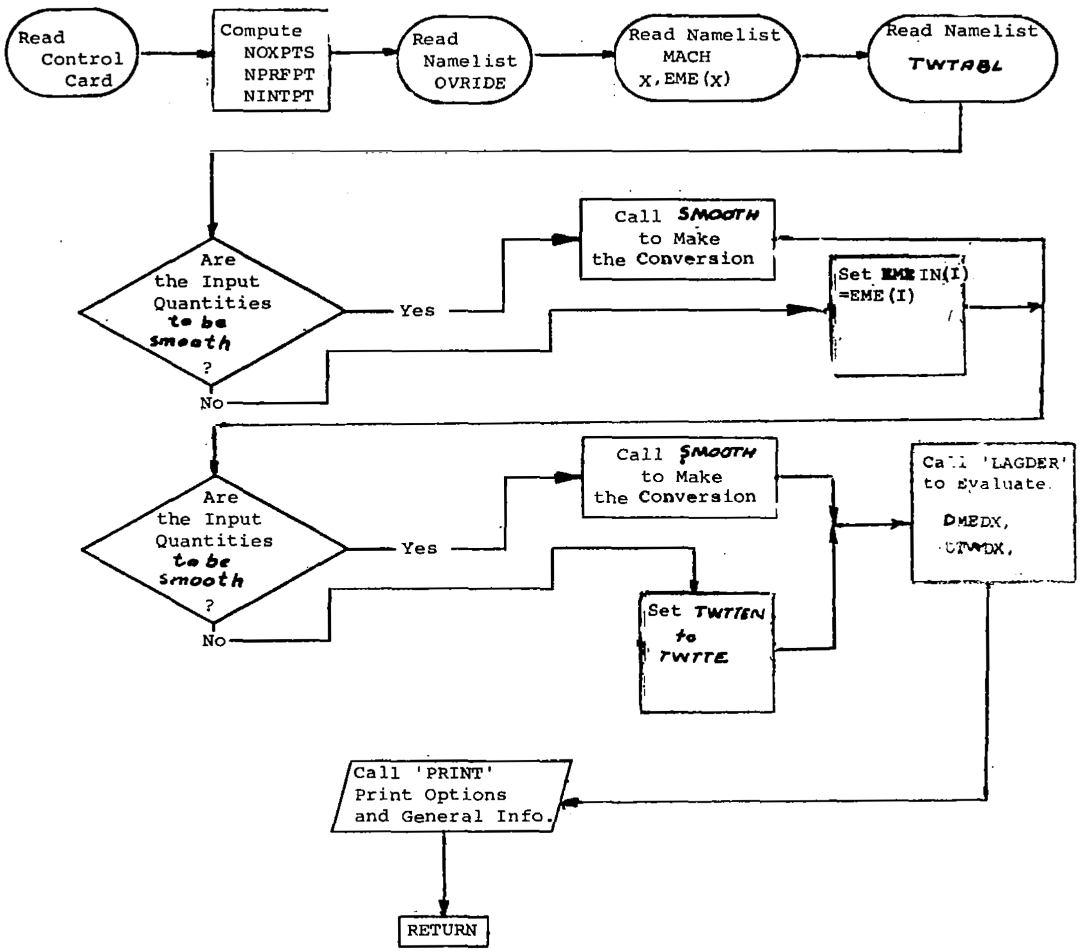
SIGMA (Σ)	nondimensional constant property displacement thickness
STILDA ($\tilde{\sigma}$)	one of Coles' scaling parameters
STLDAO ($\tilde{\sigma}_o$)	initial value of the above dependent variable
SGTLDA ($\tilde{\sigma}$)	equivalent to STILDA (used in certain portions of the calculations with this name)
STLDAP ($\tilde{\sigma}'$)	derivative of STILDA
SGMATLDA ($\tilde{\sigma}$)	equivalent to STILDA (to represent this variable in the output array)
TWALL (T_w)	the wall temperature - ^oR or ^oK
TWALLO ($(T_w)_o$)	initial value of the wall temperature - ^oR or ^oK
TTILDA (T)	ratio of the temperature at point y/L in the boundary layer to the temperature of the external flow at point, XLI
THETA (θ)	physical momentum thickness
TAULAW	relative error in RBAR calculation
TAUSTR	output array defining value of shear at $\bar{\eta}^*$
TSLDA ($\tilde{T}_s$)	value of $\tilde{T}$ at sublayer height
TT/TTE (T_T/T_{E_e})	stagnation temperature ratio at point y/L in the boundary layer
UE (U_e)	the local external velocity - ft/sec or meters/sec
UEO (U_e)	the initial or reference value of UE
UEBAR ($\bar{U}_e$)	the local external velocity normalized with respect to UEO - a dependent variable
UEIN	table of local values of external velocity input via SPEED namelist, ft/sec

UE (u_e)	the array of smoothed values of the input external velocity. If no smoothing is done this array contains the same information as the UEIN array.
UPLUS ($\bar{u}^+$)	output array defining local values of $\bar{u}/\bar{u}_\tau$
UGEN ($\tilde{U}$)	output array defining local value of Stevenson's generalized velocity
UDIF	output array defining difference in edge and local values of Stevenson's generalized velocity
USTLDA ($\tilde{u}_s$)	non-dimensional velocity at sub-layer height
UTLDSR ($\tilde{u}$*)	value of $\tilde{u}$ at $\bar{\eta}^*$
VBAR ($\bar{V}_w$)	wall blowing value in constant property plane non-dimensionalized with initial constant property external velocity
VBARO ($\bar{V}_w$)$_o$	initial value of VBAR
VWPLUS ($\bar{v}_w{}^+$)	wall blowing value non-dimensionalized with shear velocity
VPMIN	defines absolute level of tolerance on VWPLUS. Absolute values of VWPLUS less than VPMIN are assumed to be zero (i.e., implying no blowing)
UBARP	derivative of the dependent variable VBAR
VBARIN	table of input values of VBAR
VBARW	output array of local values of VBAR
VTLDAI ($\tilde{v}_w$)	wall blowing value in constant property plane non-dimensionalized with local constant property external velocity
VTLDAO ($\tilde{v}_o$)	initial value of $\tilde{v}$
WBARI ($\bar{W}$)	local value of T_w/T_{T_e}
WETA ($w(\eta)$)	wake function
XO(x_o)	the initial starting or reference value of X

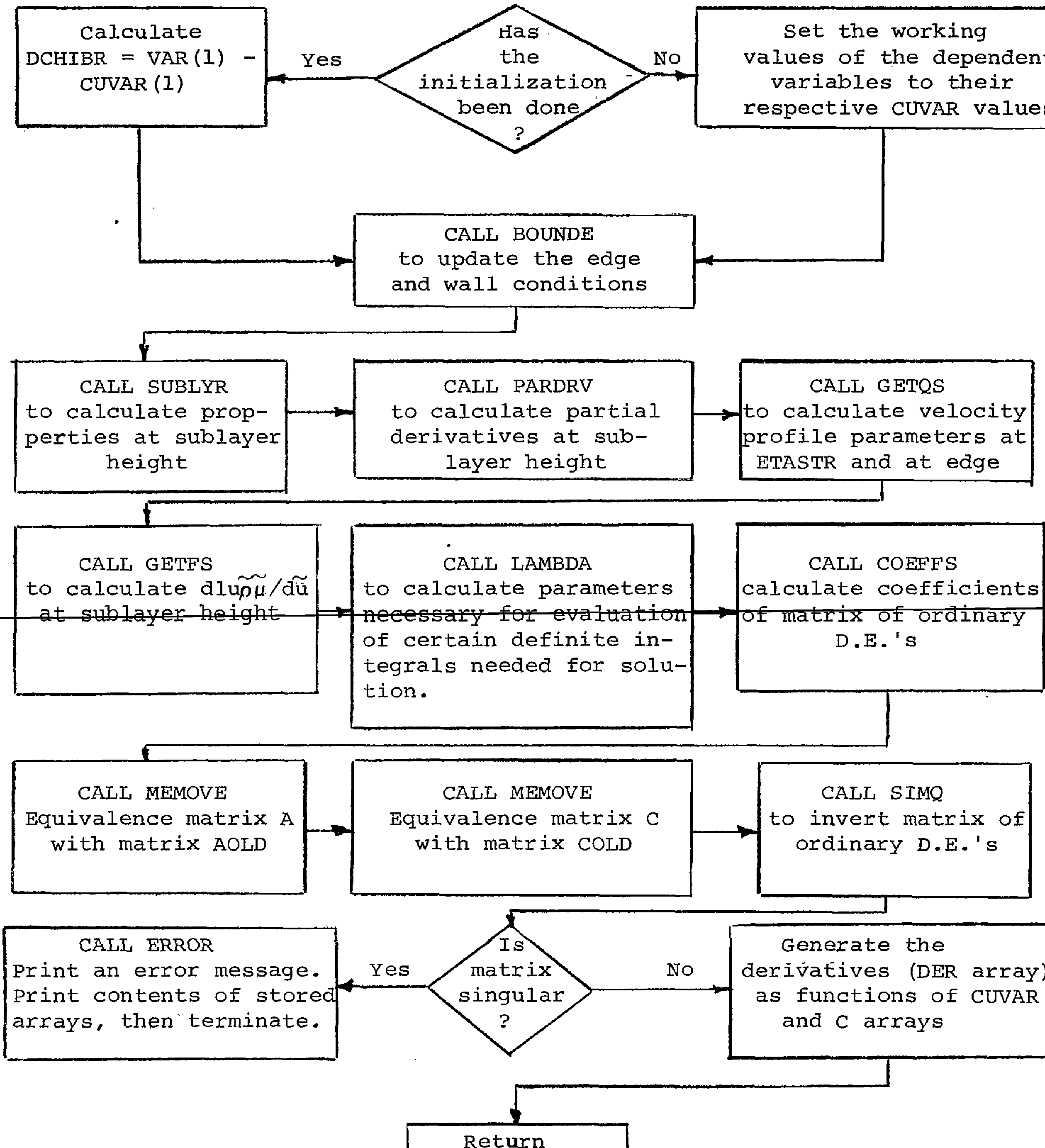
XPROFL	the 1-D array of user-prescribed values of X, RE_θ or REX at which profiles are to be computed
XEL $(x/L)_e$	table of (x/L) values corresponding to input EMEIN table
XLI	local value of non-dimensional axial coordinate
XLO $(x/L)_o$	initial non-dimensional starting distance, for calculation
XTWL $(x/L)_w$	table of (x/L) values corresponding to input TWTTEN table
YLOC (y/L)	local values of y/L for PILOT2 or local value of y (ft or meters) for PILOT1
YSPLUS $(\bar{y}_s^+)$	a transformed Reynolds number based on sublayer height and shear velocity
YPLUS	output array of $\bar{y}_s^+$
ZBAR $(\bar{Z})$	wall value of blowing parameter $\varphi^2\ \bar{V}_w/\bar{U}_e$
ZBARS (Z_s)	sublayer value of " " "
DZBARS	relative error on $\bar{Z}$
ZETA1	output array defining $\tilde{v}_w/\bar{c}_f/2$
ZETA2	output array defining $\tilde{v}_w/(\bar{c}_f/2+\tilde{v}_w)^{\frac{1}{2}}$


SUBROUTINE MAIN
Set All Internal Program Switches to their Initial Values
Zero-Out the XPROFL and DUMPSW Arrays
Call 'INPUT' to Read All Input Data
Calculate KTEST
Is the Order of Any Interpolation Scheme to be Changed?
No
Yes
Change the Order of the Indicated Parameters
Compute Three Points in the Integration Where the Trace Sequence is Changed
Is Output to be in International Units?
Yes
No
Write TESTRM
Write TESTER
Does the User Desire to Check the External Conditions?
Yes
STOP
No
Initialize the Working Values of the Dependent Variables
Set Up The Var Array for the Integrator
Call 'INTIA' (i.e. the Integration Package)
Store the Results of the Integration in the Y and YDOT Arrays
Call 'INIT2' to Calculate Req'd Program Constants & RBARO & STLDAO
Set all Working Dependent Variables & Their Derivatives to their Respective Y and YDOT Values
Has the Integration Been Performed Successfully ?
Yes
NO
Call ERROR and TERMINATE
Call 'BLPROP' to Calculate all the Boundary Layer Properties
Does the DUMPSW Array Contain A Number Other Than Zero?
No
Yes
Increment the Dump Counter
Is the Dump Counter Up to the Desired Integration Step?
Yes
No
Increment the Dump Switch Setting
Is Subroutine 'MAIN' Being Traced?
Yes
No
Turn Off All Tracing Switches
Turn on All Tracing Switches
Is the Print Control Counter Equal to the Current Value of the Integration Step Counter?
No
Yes
Calculate the Working Value of the Print Control Counter KOUNTR=NINTPT-KTRBMP
Increment the Integration Step Counter
Increment KTRBMP
Store All Values for 'X' Dependent Quantities in the Output Array, OUTARY, for this Integration Step
Increment the Print Block Size Counter
Call 'ERROR' and Terminate the Program
Has the Maximum Value of the Stream-wise Reynolds No. Been Exceeded ?
Yes
No
Has the Maximum Value of the Skin Friction Parameter Been Exceeded ?
Yes
No
Is the Print Block Size Counter Equal to KTEST?
Yes
No
Set KINTRL = 1
Call 'INTIA' to Continue the Integration
Call 'OUTPUT' to Print Present Contents of OUTARY
Call 'PRFILE' to Generate Any Profiles Which Have Been Requested
Has CHIMAX Been Exceeded ?
Yes
No
Return to the Beginning of this Routine to Start a New Case
STOP
Has a Short Print Block Been Requested ?
No
Yes
Reset the Print Control Counter, Set KINTRL = 0, Transfer OCLD to O
Restart the Integration

SUBROUTINE INPUT



SUBROUTINE DERSUB



NASA-Langley, 1972 —— 8 CR-1925